STUDY OF THE ACTUAL IGNITION SOURCES OF CLOTHING

A THESIS

Presented to

The Faculty of the Division of Graduate Studies and Research

By

Oscar A. Naveda

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Mechanical Engineering

Georgia Institute of Technology

June, 1974

STUDY OF THE ACTUAL IGNITION SOURCES
OF CLOTHING

Approved:

W. Wulff, Chairman

R. Evans

W. Tincher

Date approved by Chairman: May 23, 1974

ACKNOWLEDGMENTS

I wish to express my appreciation to those who have contributed to the completion of this thesis.

I greatly acknowledge the technical advice of Dr. Wolfgang Wulff.

I thank the Latin American Scholarship Program of American Universities and the Universidad del Zulia for their sponsorship.

I thank the National Science Foundation for funding this research under Grant GI-31882.

I thank the members of the technical staff of the School of Mechanical Engineering, all of whom contributed to this project at one time or another.

Finally, I thank my wife, Amanda, for her devotion and patience.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

SUMMARY

The purpose of fabric flammability studies is to reduce the fabric-related burn injuries and associated economical losses. These studies will produce meaningful standards via the relationship between test methods and fabric behavior in actual use.

The burn injury probability is taken as the quantitative measure of fabric fire hazard. Its evaluation depends upon the probabilities associated with the possible events leading to an injury. Two relevant events are the fabric exposure to an ignition source and the ignition of the fabric.

A first attempt is made for developing the fabric flammability conceptual framework. Principles for connecting laboratory and field test results are discussed.

The fabric ignition probability after given exposure was determined under known laboratory conditions. The results show that, at 30% relative humidity, the greater the radiative heating intensity, the lower is the mean ignition time of fabrics and the standard deviation of mean ignition time and ignition time itself, and thusly, the narrower is the 95.5% confidence interval of ignition time. At 90% relative humidity, some deviations from this tendency were observed.

Actual ignition sources were characterized to relate

laboratory to actual use conditions. They were characterized in terms of spatial heat flux and temperature distributions. The heat flux falls off rapidly with distance from the source.

The evaluation of actual fabric ignition probability requires time studies to determine garment residence times near typical ignition sources, for typical activities, age groups, etc.

CHAPTER I

INTRODUCTION

Significance of Garment Fire Injury

The enormous amount of deaths, injuries, and property losses resulting from fire accidents has promoted an arduous effort on the part of government and industry to reduce the losses from unwanted fires. In spite of the scarcity of detailed statistical information, global estimates of annual fire losses are: 12,000 Americans lose their lives and more than $11 billion in resources are wasted [1].*

The U. S. Department of Health, Education and Welfare (HEW) in its annual report of 1972 [2] assesses that there are 3,000 to 5,000 deaths and 150,000 to 250,000 injuries annually resulting from fabric-related burns, and that the direct financial loss due to flammable fabrics surpasses a quarter billion dollars. These figures do not show any significant changes from those reported in the previous 1971 Annual HEW Report [3].

In general, fabrics in garments become most frequently ignited, several times more than fabrics in bedding and furnishings [2,3,4].

It is now clearly seen that fire accidents involving

---

*Numbers in brackets designate references listed in the Bibliography.

garments are one of the major fire problems. Furthermore, it has been stated [3] that the ignition of flammable fabrics either causes a burn injury or contributes to the severity of burns sustained by the victims.

Research Objective

The purpose of fabric flammability studies is to reduce the fabric related burn injuries and their associated economical costs. One course of action to achieve that goal is the establishment of rational and reasonable standards. These standards must satisfy all those who are concerned, that is, they must be acceptable to manufacturers, retailers, consumers, and enforcement officials. The required legislation must then rest on research findings.

The Government-Industry Research Committee on Fabric Flammability (GIRCFF) formulated [5] a statement which is regarded to be the central problem of fabric flammability studies. It says:

> The determination of the relationship between fabrics in a test method, on the one hand, and the hazard it presents in actual use, on the other hand, is necessary to develop meaningful standards.

Problem Formulation

It was proposed by M. Tribus [6] that the fabric flammability problem can be approached as one of decision making under uncertainty and that the above relationship can be evaluated in terms of probability.

GIRCFF stated that there were two probabilities of extraordinary importance on Tribus' proposal, namely, the probability of burn injury after given ignition, P(B/I), and the probability of ignition after given exposure, P(I/E). The determination of P(I/E) was deemed to be "an enormous step forward in our understanding of the relationship between material performance and hazard," whereas with respect to P(B/I), "The determination of this function for various levels of fabric flammability would be one of the most desirable outcomes of the present work."

Later Evans, Wulff, and Zuber [7] showed how the aforementioned probabilities can be developed from modeling analysis and experiments.

The majority of the fabric properties needed in the evaluation of the fabric ignition probability, P(I/E), and the burn injury probability, P(B/I), have been identified and measured. Also, collection of fabric fire accident data is being carried out. However, very little effort has been done about the stochastic behavior of people around potential ignition sources, or in other words, the actual use of fabrics. The stochastic behavior of the fabric materials is still undetermined. The laboratory evaluation of the two probabilities sought has not been achieved yet.

This work is an effort to fill the existing gap in the understanding of the relation between real life situations and the experiments carried out in the laboratory. It is concerned, firstly, with the prediction of the probability of fabric ignition after given exposure, P(I/E), under fixed laboratory conditions and the measure of random fabric behavior; secondly, with the characterization of the actual ignition sources; and finally, with the actual probability of fabric ignition and its correlation to the laboratory results.

The first part is met by measuring ignition time frequencies and using a sensitive testing method called Probit Method of Analysis; the second one, by determining the spatial heat flux and temperature distributions in the vicinity of the heat-producing elements of several potential ignition sources; and the last one, by developing the mathematical formalism to connect, in principle, the fabric ignition probabilities under actual and laboratory conditions.

It must be emphasized that the purpose is to present the principles of fire hazard assessment rather than gathering a vast amount of statistical data and obtaining numerical results for actual probabilities.

This research is part of the fabric flammability studies conducted at the Georgia Institute of Technology (GIT) since 1970. These studies have been supported by three grants from the National Science Foundation (NSF) under the Research Applied to National Needs (RANN) program. The work has been monitored by GIRCFF during its first two years. Other institutions participating in this program were: The

Massachusetts Institute of Technology (MIT), The Factory Mutual Research Corporation (FMRC), and The Gillette Company Research Institute (GCRI).

CHAPTER II

PREVIOUS EFFORTS AND ACCOMPLISHMENTS

Legislative Action

The problem of flammable fabrics has been one of great concern for a long time. It was nationally recognized in 1953 when the Flammable Fabrics Act (FFA) was passed. Fourteen years later, in December of 1967, that Act was amended due to the need for more rigorous and stricter regulations. The FFA as amended delegates to the Secretary of Commerce the responsibility for conducting research on the flammability of products, fabrics, and materials; for conducting studies on the feasibility of reducing their flammability; for developing flammability test methods and testing devices; and for offering training in the use of those methods and devices [8].

A Government-Industry Research Committee on Fabric Flammability (GIRCFF) was created by the National Bureau of Standards (NBS) for coordinating research efforts of government, industry and universities. It was for two years in charge of formulating and administering sponsored research programs designed to develop the technical and scientific basis for making the required changes in the actual standards.

The Information Council on Fabric Flammability (ICFF) was also formed. It works toward the reduction of morbidity and mortality from burns caused by flammable fabrics and related materials by encouraging the exchange and dissemination of information such as injury statistics, research findings, testing methods, and public information programs.

Development of Standards

The current standard on fabric flammability is the commercial standard CS-191-53. In this test, the specimens are placed into an apparatus at the angle of 45°. The fabric's surface is impinged by a small flame for one second. The fabric fails the test if the specimen ignites and burns a five-inch length in less than four seconds. It is basically the measurement of ignition time and flame propagation speed. Slow burning has always been associated with relative high fire safety, however, there is no definite basis for this argument. Human behavior must be taken into account for setting more reliable standards.

New standards are urgently required for giving better protection to the public against hazard of fabric related burn injury.

During the years of 1970 through 1971 three new standards were established by the Secretary of Commerce [8,9] concerning carpets and rugs, and children's sleepwear. Likewise, a standard for mattresses has been proposed and a flammability test method developed for blankets. A short description of those is given next:

(1) <u>Standard DOC FF 1-70, Surface Flammability of Carpets and Rugs</u>. This standard is designed to protect the public from the occurrence of carpet and rug fires from small ignition sources, such as matches or fireplace embers. It applies to carpets and rugs larger than 24 square feet or having one dimension greater than six feet. Eight conditioned, identical specimens are exposed to a standard ignition source and the extent of char formation is measured. A specimen passes the test if the charred portion does not extend to within one inch of the edge of the opening in the flattening frame. At least seven of the eight specimens must meet the test criterion in order to conform with this standard.

(2) <u>Standard DOC FF 2-70, Surface Flammability of Carpets and Rugs</u>. It applies to small carpets and rugs. The flammability test is the same as before, but it is more flexible in its application, allowing for the sale of small carpets and rugs, if properly labeled.

(3) <u>Standard DOC FF 3-71, Children's Sleepwear</u>. Fabric specimens are 3-1/2 x 10 inches and they are hung vertically in the test chamber. The flame impingement time at the bottom edge is for three seconds. The criterion for specimen acceptance is based on the char length and the burning time of drips or other fragments on the floor of the test chamber. They must not exceed seven inches and 10

seconds, respectively.

(4) Proposed Standard for Mattresses. This standard evaluates the resistance of mattresses to ignition by cigarettes. Single cigarettes are placed at three specified locations and burned on the bare mattress, and with cigarettes between two sheets on the mattress. If any one of the cigarettes ignites the mattress, that mattress fails to meet the standard.

(5) Developed Flammability Test Method for Blankets. This is also a test to measure resistance to ignition. The test specimen is circular and 2-1/2 inches in diameter. A small flame impinges on the center of the specimen for one second. The specimen must not ignite in order to satisfy the standard.

The children's sleepwear standard applies only to apparel of children in the age range between 0-5 years. Lately it has been found that the accident rate for children 6-12 years old is as much as that for children 0-5 years old [10]. Consequently, an amendment on the Standard DOC FF 3-71 is required to include clothing of children up to 12 years old.

General information on any standard can be obtained from References [11,12].

Research Findings

The scientific problem of fabric flammability assessment is, in principle, solved when the burn-injury probability can be predicted.

Zuber and Wulff [7] showed how modeling techniques and experimentation can be used for estimating the above probability. They noticed that certain processes associated with flammability of fabrics are transient in nature such as conduction, convection, radiation, internal chemical reactions, desorption of moisture. Relevent time scales characterize these processes. The variable time is the clue to the problem. The fabric ignition time and the exposure time are the two characteristic time elements. The ignition time is the time directly related to the physiochemical processes involved in the destruction of fabrics. The exposure time is the representation of the random behavior of people in the presence of any potential ignition source.

The studies in the field of fabric flammability have mainly been oriented toward the modeling analysis and experiments relevant to the prediction of ignition time [13,14], the flammability of clothing assemblies [15], and the prediction of burn damage potential of clothing fabrics [16].

Particularly, at GIT, a complete modeling analysis for the purpose of determining the relevant modeling rules needed to predict the ignition time was achieved [13]. The model consists of a heating source, the fabric, and the human tissue separated from fabric by an air gap.

The analysis took into account fabric material properties, physical processes such as the heating mode and boundary conditions, and different geometries. It provides the rules of partial modeling and an assessment of the associated errors. The definition of suitable experiments for predicting the ignition time is also accomplished by the analysis.

Further studies have been performed incorporating the chemical effects of desorption and pyrolysis and are being developed in order to find a better agreement between the experimental results and the analytical prediction of the ignition time. Some results appear in Reference [14].

Experimentally, the ignition time of single fabrics has been measured under radiative [13], and under gas flame heating at GIT [14,17] and at FMRC [18]. The fabric ignition time turned out to be dependent on fabric properties and exposure conditions, chiefly on the heating intensity level. The convective heat transfer from the flame to the fabric is the dominant mechanism that dictates the fabric ignition time under gas flame heating.

Cumulative frequency distributions were obtained in terms of ignition times under gas flame heating at GRCI [19].

However, the problem of flammable fabrics should also be approached through education programs on fire safety. The National Commission on Fire Prevention and Control found [1] that the majority of fire accidents are due to the carelessness of people, largely through lack of concern and ignorance of hazards.

McDonald, Dardis and Smith [20] included in their work the educational aspect on Flammable Fabric studies by means of decision theory. They considered protective clothing and education in their effort to find the level at which a flammability standard is cost-effective. They found that the above variables are interdependent.

It should be made clear that Tribus was only concerned with the level at which the standard must be set. A later effort on setting the level of a standard is due to Craw [21]. It is a status report based on Tribus' paper, emphasizing the need for determining the conditional probabilities and suggesting some sources of information.

Another approach is based on a short investigation [22] of peoples' behavior around kitchen ranges. It resulted in the recommendation of design principles for kitchen ranges to reduce fire hazard.

Other aspects of the fire problem are the production of smoke and toxic gases even if the material is fire retardant. A quantitative measured of smoke hazards is due to Gaskill [23].

Collection of Statistics

It was realized very early that the statistics on fabric related burn injuries are inadequate and meager. The Injury Statistics Committee of ICFF [24] undertook to solve this problem by listing the sources from which data on mortality and morbidity associated with ignition of clothing and household furnishing could be obtained.

During the Second Annual Meeting of ICFF in 1968, the first two studies on fabric ignition statistics [25,26] were presented. A set of ignition sources which contains all currently relevant ignition sources was recognized. Elements of that set are kitchen ranges, smoking materials, open flames, flammable liquids.

McDonald, Dardis and Smith [27] developed and evaluated procedures for obtaining information on circumstances associated with fire injuries and the cost of such injuries. The more frequent ignition sources were found to be the same as before and dwelling units were found to be the most frequent location of fire injury. Textile products were the primary agent ignited. Apparel items were most frequently ignited by the young group, 0-9 years old, and the elderly group, 65 years old and over. It was also established that there are many cultural and sociological factors affecting the frequency with which accidental burns occur.

Detailed studies have lately been conducted by the Department of Health, Education and Welfare (HEW) in order to obtain reliable statistics at a national level. The National Bureau of Standards has created the Flammable Fabrics Accident Case and Testing System (FFACTS). These two data collection centers work in continuous cooperation as required by the Flammable Fabrics Act (FFA).

The Third [2] and the Fourth [3] Annual Reports of HEW are among the most reliable and complete sources of statistical fire accidents information we have available to assess the frequency of fabric related burn accidents. The data has been classified with respect to age and sex of the victim, physical handicap, time of day, general and specific location, victim activity or combination of these factors. Also, the type of fabric usually involved is discussed.

The collected data is not statistically significant yet.

A condensed summary of the statistics found in the Third and Fourth Annual Report of HEW is shown and discussed next.

In the summary are considered only three age groups: children up to 14 years old, adults between 15 and 64 years old, and the group of the elderly, 65 years old and over.

Table 1 shows the percentage distribution of fabric fire accidents by age and sex of the victim. It can be seen that accidents involving male victims are more frequent than those involving females except for the elderly group.

The location of the accidents was, in 884 out of 1,233 cases, the victim's residence, i.e., in 71.7% of all cases for which the location of the accident was reported. Specifically, the most frequent locations were found to be the bedroom, living room, kitchen and yard, which accounted

Table 1. Percentage Distribution of Fabric Fire Accident Cases by Age and Sex of the Victim

Age of Victim	TNC = 1227; Year: 1971		TNC = 1659; Year: 1972	
	Male	Female	Male	Female
0-14	18.4	15.8	19.5	16.5
15-64	32.5	18.6	29.5	20.3
64-over	5.8	8.9	5.6	8.6
	56.7	43.3	54.6	45.4

Source: HEW Flammable Fabrics Annual Reports
TNC: Total Number of Cases Known.

for more than two-thirds of the cases.

Table 2 indicates clearly the leading activities of the victim at the time of the fire incident. Ranges, open flames, and smoking material produce almost 75% of the fabric ignitions, see Table 3. Other sources are furnaces, space heaters, hot water heaters, candles, electrical wiring, machine tools, etc. Gas range accidents are about twice as frequent as electric range accidents.

Garment fabric accidents are several times more frequent than fabrics in bedding and furnishings.

Because of the frequent incidence of fabric fires caused by matches and lighters, a summary and an analysis of the related accidents has been made and published by NBS [28].

Summary

The direct damage caused by a fabric fire is either death or a burn injury, the severity of which is measured by the depth of tissue destruction and the total area burned, or by the destruction of the respiratory system.

Three alternatives have been suggested to reduce losses from apparel fires. They are: changes in the existent standard or creation of new ones to modify garments, educational programs to increase the awareness of the public toward the fire hazard in general, and modifications of the design features of potential fabric ignition sources.

Table 2. Victim Activity

Victim Activity	Year: 1971 TNC: 1196	Year: 1972 TNC: 1554
	Fraction of TNC	
Cooking	12.1%	--
Cooking (no stove)	--	1.0%
Climbing on or near top of stove	--	1.5
Reaching across stove	--	5.5
Leaning against stove	--	3.0
Standing to close to stove	--	4.1
Lighting oven/burner/pilot light	--	2.5
Playing with matches	10.5	11.3
Being around an open fire	13.0	7.8
Fell asleep while smoking	7.6	6.4
Using matches/lighter	10.5	7.5
Smoking	5.8	10.0
Cleaning flammable liquid	2.7	2.8
Total	62.2	63.4

Source: HEW Flammable Fabrics Annual Reports

TNC: Total Number of Cases.

Table 3. Heating Source of Ignition

Ignition Source	TNC = 1187; Year: 1971	TNC = 1546; Year: 1972
	Fraction of TNC	Fraction of TNC
Kitchen Ranges	20.1%	19.2%
Open Fires	13.2	11.8
Smoking Material	40.9	41.1
	74.2	72.1

Source: HEW Flammable Fabrics Annual Reports

TNC: Total Number of Cases.

The ignition time of single fabrics and the thermophysical properties which characterize the ignition process have been measured under radiative and convective heating mode at several research centers. Mathematical models have also been developed.

Information on fire accidents involving flammable fabrics have been collected and analyzed. The most common ignition sources are now clearly recognized.

CHAPTER III

REQUIRED ADVANCES

The determination of the fabric ignition probability is an enormous step forward in the solution of the fabric flammability problem.

Wulff, et al. [7] showed that the fabric ignition probability can be expressed in terms of: (1) physical properties and geometry of the garment, (2) physical process parameters, describing process conditions, and (3) human responses and reactions. The first two items involve the assessment of the fabric ignition time, while the last one is concerned with the exposure time to an ignition source. Furthermore, the probability of fabric ignition after given exposure can be expressed as the function of the ratio of exposure time τ_e over ignition time τ_i, thus

$$P(I/E) = f(\tau_e/\tau_i) \tag{3.1}$$

Since the ignition time of single fabrics has already been determined under radiative and convective heating modes, and statistics on fabric fire incidents are being collected, the determination of the fabric ignition probability can, in principle, be attempted.

The required advances for its determination can be summarized as follows:

(1) Information Retrieval and Evaluation. The hazard from flammable fabrics is to be expressed in terms of probabilities. Probabilities required for the hazard assessment must be supported by statistics from burn injury data, fabric supply data, and exposure time studies.

However, compilation of data has only been oriented toward gathering of information on serious accidents.

Exposure time studies are required in order to predict the random behavior of individuals in the vicinity of potential ignition sources. The same observations will produce the use frequency of ignition sources, the frequency of exposure and exposure durations.

Fabric supply data will reveal the fraction of a given fabric which is sold and converted into a specific garment.

(2) Detailed Decision Tree. M. Tribus proposed a decision tree to attack the problem of fabric flammability. This decision tree is not exhaustive yet. Therefore, it must be revised and eventually expanded. However, a decision tree's expansion must be rational since there exist a compromise between the introduction of new variables and the cost required for their evaluation.

(3) Laboratory Fabric Ignition Probability. The laboratory fabric ignition probability is to be determined which can readily be achieved by ignition time frequency

measurements under well-defined laboratory conditions.

(4) Actual Fabric Ignition Probability. The actual ignition probability is, in principle, determined once we know the actual exposure conditions. Real life ignition sources do not have the same hazard potential as the laboratory sources, i.e., they have different heating intensities and exposure conditions. It is also clear from experience that all fabrics are not exposed with the same relative frequency to the same exposure conditions.

Hence, a study of actual ignition sources characteristics and the stochastic behavior of people in the neighborhood of ignition sources are required for the evaluation of real life fabric ignition probability.

(5) Correlation of Laboratory to Actual Fabric Ignition Probabilities. The GIRCFF's statement seeks a relationship between test methods and actual behavior of fabrics. Hence, the real life and laboratory fabric ignition probabilities are to be correlated.

This work deals with the general principles for fire hazard assessment, with the determination of the laboratory fabric ignition probability, with the evaluation of ignition source characteristics, with the actual fabric ignition probability evaluation, and, briefly, with the correlation of laboratory and actual ignition probabilities.

CHAPTER IV

PRINCIPLES OF FIRE HAZARD ASSESSMENT

Quantitative Measure of a Hazard: Burn Injury Probability

The reduction of losses from unwanted fires by means of legal restrictions imposed on ignition sources and combustible materials invariably involves flammability standards which require the execution of standard tests.

The logical connection between test methods and the hazard that a material, such as a fabric, presents in actual use can be achieved only after a quantitative measure of the potential burn injury hazard has been established.

Decision theory is concerned with the logical analysis of choice among alternative actions in the face of uncertainty. The uncertainties that may be dealt with are the connection between alternatives and the set of possible outcomes or it may be related to reliability of the available information. Decision and probability analysis can be used to determine the likelihood of the expected outcomes once a course of action has been selected and to make a final judgment based on the comparison of the results obtained for every alternative.

In fire hazard assessment, the set of possible standards to be proposed constitutes the alternatives or courses of action, whereas the occurrence of a burn injury is the ultimate outcome expected.

Therefore, the burn injury probability, as proposed by Tribus, is a quantitative measurement of the hazard represented by a given fabric or material in general use which satisfies the requirements of a standard.

Deterministic Events

An event is said to be deterministic when it depends uniquely on a set of causes. In other words, there is a unique relation between a set of variables such that if all, except one, are specified the remaining variable is readily deducted and it is represented by a unique value. All the physico-chemical events of ignition, flame spread, extinguishment and tissue destruction fall in this class.

Stochastic Events

When there is no known cause-effect relation from which the answer may be deduced but a set of likely values is expected from which the answer may be drawn, the relation is said to be stochastic. These situations are basically problems of inductive logic and always leave uncertainty in our minds. Human choices and human responses related to unwanted fires are classified as stochastic events.

Prediction of Burn Injury Probability

In principle, the technical aspect of the fabric flammability problem will be solved once one has determined the fabric burn injury probability resulting from the adoption of a certain standard.

However, the direct evaluation of the burn injury probability conditional to the selection of a standard S_i, $P(B/S_i)$, is impossible because a series of events leads to the burn injury, every one of which has its own subprobability of occurrence.

Probability analysis provides the tool to combine the subsidiary probabilities. Intermediary events for which the evaluation of the conditional probabilities are easier to find must be introduced between the standard and a burn injury. This introduces the decision tree or tree diagram.

Once the estimation of the intermediate probabilities is carried out, the computation of the overall probabilities for every possible succession of events must be performed.

Finally, the summation of all overall probabilities represents a rational measure of the burn injury probability.

<u>Decision Tree</u>

A decision tree for the prediction of the burn injury probability must include all the alternatives, i.e., standards; the set of possible outcomes, i.e., any possible degree of burn injury, and the set of intermediary events which will facilitate the evaluation of the probability sought, $P(B/S_i)$.

One expands Tribus' decision tree [6] to determine how the collection of information must be organized for several levels of progress that each event can reach. One should not split the decision tree further than is necessary, because of the cost involved in the gathering of reliable information.

We have basically two stochastic types of events:

(i) Selection events for which probabilities can be expressed in terms of relative frequencies. These include consumers' decision and suppliers' replies to consumers' wishes, and

(ii) the Physicochemical process which are all transient in nature and dependent on characteristic times. They start with the fabric exposure to an ignition source and lead through fabric ignition to combustion, flame spread, and tissue destruction.

Figures 1 and 2 below show the expanded decision tree. Figure 1 accounts for the selection events, while Figure 2 deals with the physicochemical events. We are only considering the adoption of one standard and one branch from each representative node for ease of explanation. No conceptual difficulty exists to accommodate additional events.

The selection events begin with the adoption of a standard which is met by several fabrics.

A fraction of an approved fabric is sold and several kinds of products are manufactured, such as clothings, tablecloths, towels, drapes, etc. The consumers will buy those products in accordance to their needs, basically a function of taste, wealth and age. The finished products must present features to satisfy the consumer. For instance,

Key: S = Standard
F = Fabric
GF = General Finished Product
G = Age Group
CC = Comfort Characteristics
C = Additional Cost

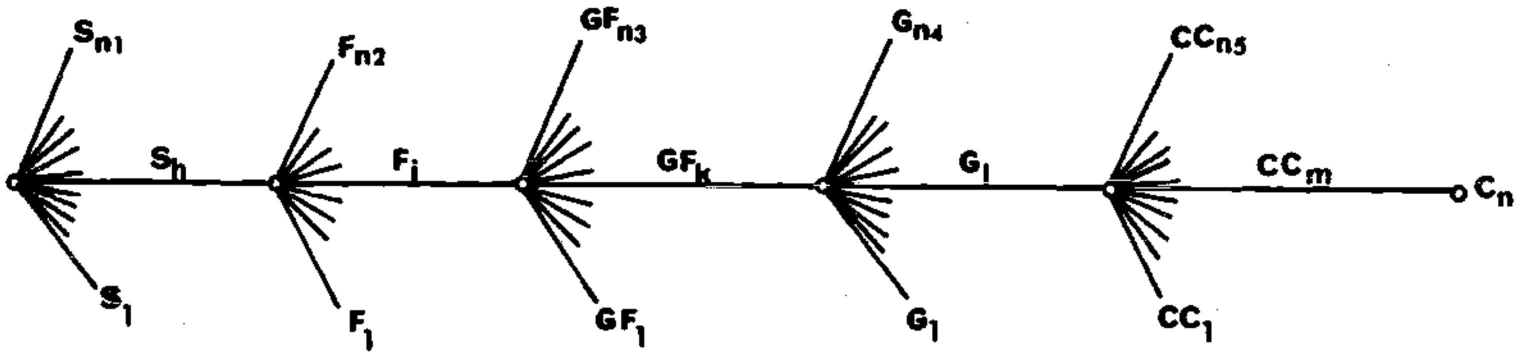

Figure 1. Decision Tree for Selection Events

Key : C = Additional Cost I = Ignition

U = Use EX = Extinguishment

E = Exposure B = Burn

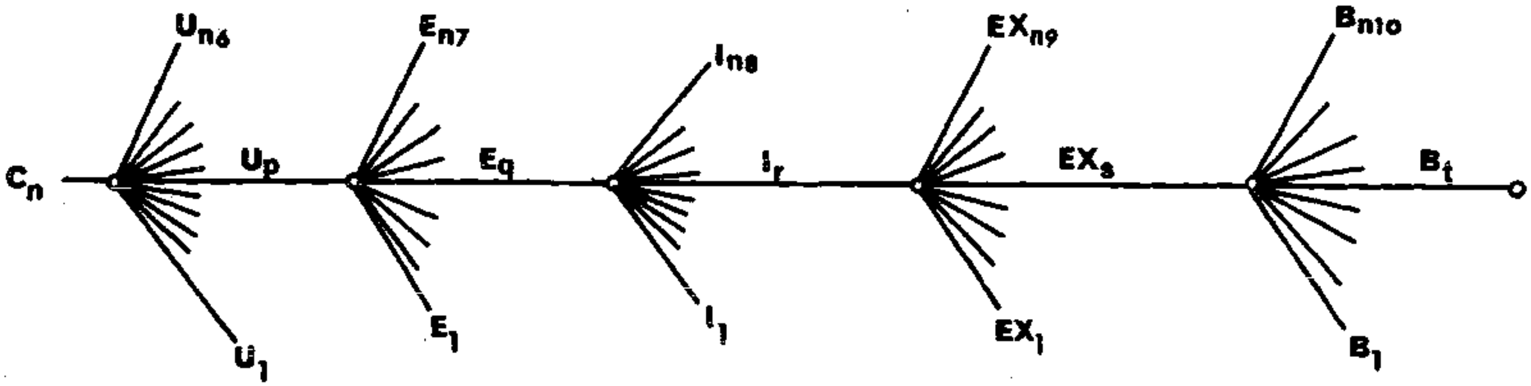

Figure 2. Decision Tree for Physicochemical Events

it must have machine washing capabilities, acceptable taylorlng styles, etc. An additional cost is, of course, charged for the manufacture of a better fire resistant material, garment design, etc.

Assuming that the consumer decides to buy the product, he will wear or use it for different activities, which will depend basically on his social, cultural and economical status. In every one of those activities the finished product might be exposed to different ignition sources or perhaps to none at all. As an eventual consequence of exposure ignition of the product can occur. Several degrees of ignition and/or equivalent problems can happen, for instance there is no ignition but production of toxic gases and heavy smoke. That condition causes injury, perhaps a burn or just asphyxia, or a combination of both.

An intermediate possible event, between ignition and combustion, and the appearance of a burn, is the flame extinguishment, possibly aided by some one other than the victim.

Probability Principles

All events leading to burn injury are to some extent stochastic. Probability concepts are then necessary for the computation of the burn injury probability.

All events, in our case, are selected, by applying the Extension Rule, to be independent of each other. That is, the occurrence of any event does not affect the occurrence of the others.

The probability of two events to occur simultaneously is expressed as:

$$P(AB) = P(A/B).\ P(B) = P(B/A).P(A) \qquad (4.1)$$

where,

$P(AB)$ = probability that events A and B occur simultaneously.

$P(A/B)$ = probability that A happens once B has occurred.

$P(B)$ = probability that B occurs.

The above equation is known as the Product Rule. Notice the symmetrical property of the product rule.

If the event A and B are independent, then we have that

$$P(A/B) = P(A) \qquad (4.2)$$

$$P(B/A) = P(B) \qquad (4.3)$$

and

$$P(AB) = P(A).P(B) \qquad (4.4)$$

The probability that any of two events occur, separated or simultaneously is given by:

$$P(A \cup B) = P(A) + P(B) - P(AB) \qquad (4.5)$$

where $(A \cup B)$ means that event A and/or B can occur. If A and B are independents, then

$$P(A \cup B) = P(A) + P(B) - P(A).P(B) \qquad (4.6)$$

$$= 1 - (1-P(A)) \; . \; (1-P(B)) \qquad (4.7)$$

Therefore, there exist fundamentally two ways or gates to relate events. They are: OR and AND gates. If the occurrence of events A depends only and the occurrence of some of or all the possible previous events B_1, B_2,..., B_i,..., B_n, then we have an OR gate and the probability is evaluated as follows:

$$P(A) = P(B_1 \cup B_2 \cup \ldots \cup B_n) = 1 - \prod_{i=1}^{i=n} (1-P(B_i)) \qquad (4.8)$$

We have an AND gate when the occurrence of the event A depends on the occurrence of all the possible previous events leading to A. Thus,

$$P(A) = P(B_1 B_2 \ldots B_n) = \prod_{i=1}^{i=n} P(B_i) \qquad (4.9)$$

Let us now suppose that we have a <u>sequence of events</u> A, B and C and we are asked to compute the probability that

C happens after A has occurred, $P(C/A)$. We assume to know a set of n independents outcomes B_i and that event B is relevant to the truth of events A and C, then we can attempt to introduce the known variable B to facilitate the evaluation of $P(C/A)$. Thus, we have

$$\sum_{i=1}^{i=n} P(B_i/AC) = 1 \tag{4.10}$$

multiplying both members of the equation 4.10 by $P(C/A)$, we get

$$P(C/A) = \sum_{i=1}^{i=n} P(B_i/AC).P(C/A) \tag{4.11}$$

using the product rule definition,

$$P(C/A) = \sum_{i=1}^{i=n} P(CB_i/A) \tag{4.12}$$

and, from the symmetry property of the product rules, we finally get,

$$P(C/A) = \sum_{i=1}^{i=n} P(C/AB_i).P(B_i/A) \tag{4.13}$$

So, we have included the auxiliary event B to make easier the determination of $P(C/A)$. This procedure is called the extension rule.

Laboratory and Field Tests

Any manufacturer always wants to know as soon as possible how his product is performing or will perform in the field. One way to accomplish that objective, in advance of large scale distribution, is by carrying out laboratory tests which represent the actual conditions. This means scaling actual conditions to suitable laboratory conditions. Thus, if one knows the test methods and the actual conditions one can predict actual use performance from the laboratory results.

Unfortunately, one cannot predict the fabric hazard in actual use because one neither has a definite experiment nor does one know the actual conditions. Consequently, laboratory and field tests are required and their correlation will afford the setting meaningful standards.

Probability of Ignition After Exposure

It was asserted that the probability of ignition is an important step to be achieved toward the understanding of fabric's behavior.

Laboratory Conditions

Laboratory tests have been carried out by simulating exposure conditions which occur, fortunately, in actual use with very low, but not negligible, small frequency. Laboratory tests are always run under fixed, specified and well-controlled conditions. Hence, the ignition probability can be obtained for every set of possible conditions.

Actual Conditions

The probability of ignition after given exposure is believed to depend, chiefly, on the heating level and the exposure time. The heating levels are different for different heat sources. The exposure times are functions of the human's response. So, in real life, there exist many more possible conditions than those studied in the laboratory. Consequently, a correlation of similar results must be performed in order to foresee the actual behavior from laboratory results.

CHAPTER V

PROBABILITY OF IGNITION UNDER LABORATORY CONDITIONS

Fundamental Parameters

The probability of fabric ignition after exposure is postulated to depend on the exposure time, τ_e, and the fabric ignition time, τ_i, more specifically, on the ratio of these times, namely

$$P(I/E) = f(\tau_e/\tau_i) \tag{5.1}$$

Ignition time has been measured for single fabrics under radiative and convective heating modes. Hence, the determination of ignition time frequencies will be necessary to:

(i) Find the statistical confidence of the ignition time data previosuly obtained,

(ii) Evaluate the laboratory fabric ignition probability.

The characterization of any random variable is achieved once we know its mean and its variance. Consequently, the determination of the fabric ignition probability rest on the knowledge of:

(i) The mean value, $<\tau_i>$, of the ignition time, and

(ii) The standard deviation, σ, of the ignition time about the mean ignition time, $<\tau_i>$.

(iii) The standard deviation, σ_μ, of the mean ignition time, $<\tau_i>$, to estimate the stochastic nature of the experiment itself.

We are concerned only with the fabric ignition probability under radiative heating.

Ignition Frequency Measurements

Apparatus

The device used is the same as employed for measurements of ignition time under radiative heating, that is, the Radiative Ignition Time Apparatus (RITA).

RITA was designed, constructed and instrumented such that a circular sample can be exposed to a uniform irradiation over a 25 mm circle, at intensities in the range between 0.25 to 20 W/cm^2. The radiant pulse has negligible transients and flame detection is automatic by infrared sensors. RITA is enclosed by a 2.54 m x 1.62 m x 2.08 m environmental chamber with temperature and humidity control.

Specifications, operating principles, and design features of RITA can be found in References 13 and 29.

The Radiative Ignition Time Apparatus is schematically shown in Figure 3. It can be operated in single or double shutter mode. The single shutter mode is used for the ignition time measurements during which the second shutter

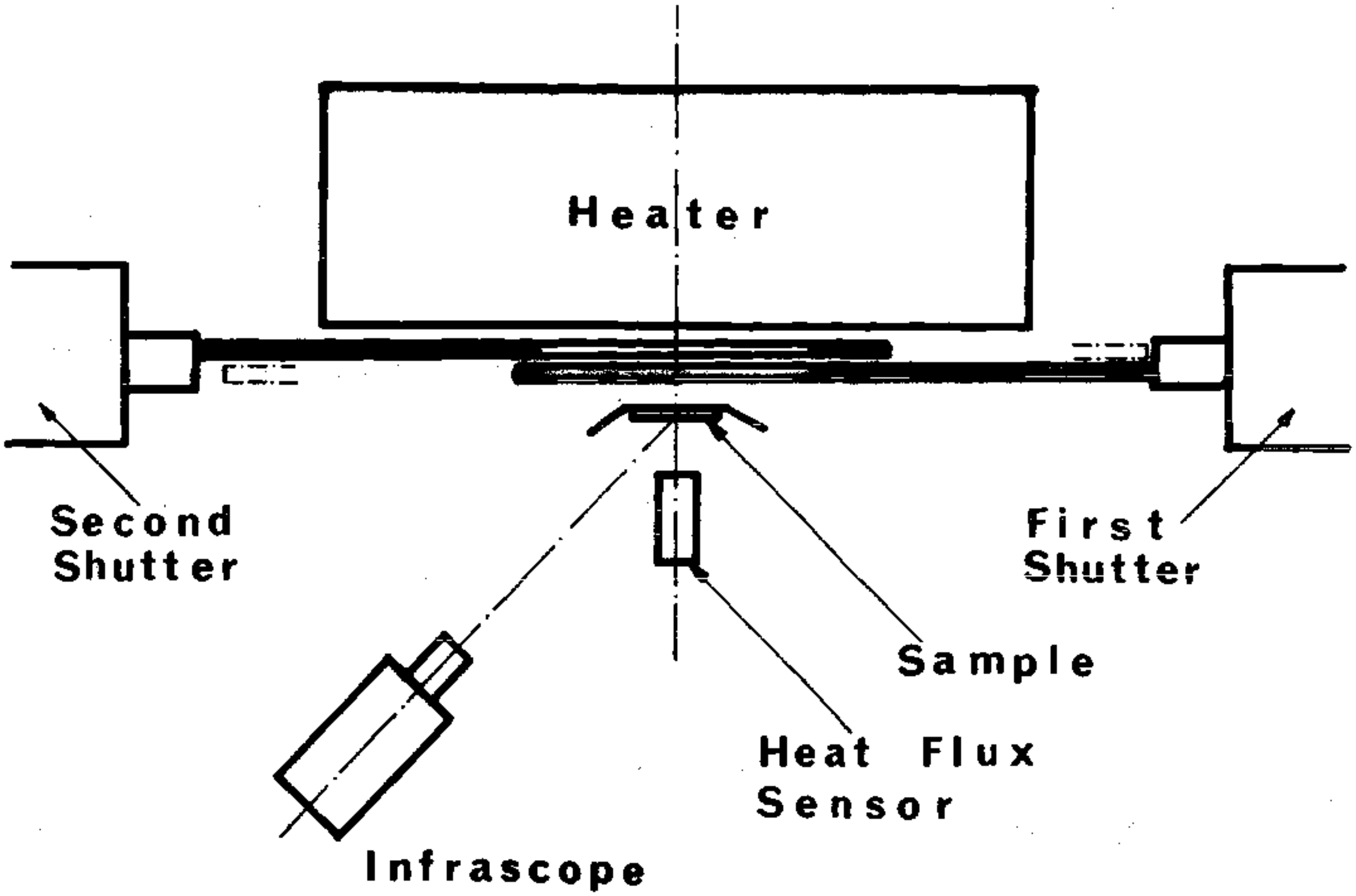

Figure 3. Schematic Representation of Radiative Ignition Time Apparatus

remains opened. Double shutter mode is used for the ignition time frequency measurements. The second shutter interrupts the radiant heat flux and with the aid of suitable timing circuits regulates the time of exposure accurately.

Fabric Ignition

The ignition of a fabric is recognized by the appearance of a flame. It is determined from the steep rise on the oscilloscope traces recorded from the infrared detector focused on the back face of the fabric. Fabric was then removed from RITA and classified as charred, ignited and burned, or melted.

Procedure

Temperature and relative humidity in the chamber are selected. The fabric is allowed to reach equilibrium within the environmental chamber for at least 12 hours. The fabric is placed in the sample holder, a preselected level of heating intensity is chosen and, after allowing the radiative source to reach steady state, exposure to the heat source begins and lasts for the preselected exposure time which is monitored with a precision of ± 0.01 seconds. The fabric is then removed from RITA, classified and recorded as destroyed or non-destroyed. Another fabric is positioned into RITA and the experiment is repeated. Exposure times were selected to vary between 0.8 and 1.2 times the previously measured ignition time τ_i, in such a way that both wings of the frequency distribution were included, that is, none and all of the fabric samples ignited.

Data Reduction

Frequency Distribution

The data obtained was condensed by constructing the frequency distribution scheme. The working range from $0.8\ \tau_i$ to $1.2\ \tau_i$ was subdivided into class intervals of width 0.02 times the previously found ignition time, τ_i, and the fraction of destruction was computed for each class. The fraction of destruction is defined as the ratio of the number of samples ignited over total number of tests.

The fractions of destruction were then plotted on normal probability paper and showed to follow fairly well a straight line. That indicates that the ignition time frequencies is normally distributed. A chi-square test was performed to prove the goodness of this hypothesis with a 95% of confidence.

Analysis

The term "sensitivity test" [30] is commonly applied to the following situations:

(i) A test item will respond or not respond to a certain level of test stimulus,

(ii) The test is eventually destructive to the item being tested, no matter what the outcome of the test, the response is irreversible,

(iii) The percentage of items expected to respond increases as the severity of the test is increased.

These three characteristics are clearly satisfied by our ignition time frequency measurements. The fabric was destroyed or not, once the fabric was tested it could not be used for another test, and as we increased the heating intensity level, the fabric failed more frequently.

The probability of ignition after given exposure turned out to be normal or Gaussian. The normal distribution is characterized by the mean value $<\tau_i>$ of the ignition time and the standard deviation σ of the ignition time, both dependent on exposure conditions such as heating mode and intensity, and fabrics conditions such as moisture content.

Thus, the fabric ignition probability conditional on laboratory exposure conditions yields:

$$P_\ell(I/E) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\lambda} \exp(-z^2/2)dz \tag{5.2}$$

where the upper integration limit λ is given by:

$$\lambda = \frac{\psi-1}{\sigma} \tag{5.3}$$

and ψ is the ratio of exposure time over mean ignition time, $<\tau_i>$, i.e.,

$$\psi = \frac{\tau_e}{<\tau_i>} \tag{5.4}$$

Even though no ignition frequencies can be observed for negative ignition times, that is, for $\lambda<-1/\sigma$, the expression in equation 5.2 represents experimental data well in the neighborhood of $<\tau_i>$ because the contribution of the integral from $-\infty$ to $-1/\sigma$ is insignificant for all values of σ observed.

Probit analysis [30,31], a sensitivity test, was then used for the simultaneous evaluation of the mean ignition time, $<\tau_i>$, the standard deviation σ of the ignition time about the mean ignition time, and the standard deviation σ_μ of the mean ignition time. A computer program was written to facilitate the fast and continuous evaluation of the test results.

Results

The grand total of 1077 tests was performed at three heating intensities and two levels of environmental relative humidity for three different single fabrics. The detailed fabric identification is shown in Table 10 in Appendix A.

Tables 4, 5 and 6 show, in their first five columns, the identification of the fabric, the irradiation levels, the relative humidity levels, the number of successful tests run for each case, and finally the ignition time measured under single shutter mode. The temperature in the chamber was always 75°F.

The last three columns contain the statistical results

Table 4. Ignition Time Statistics

GIRCFF Fabric No.	Irradiation W_o	Relative Humidity	Number of Tests	Ignition Time		Standard Deviation of Ignition	
				Single Shutter	Median	Mean	Time
				τ_i	$\langle\tau_i\rangle$	σ_μ	σ
	W/cm^2	%	--	s		s	s
5	6.50	30	77	31.00	31.45	0.37	2.53
5	9.52	30	25	13.35	13.13	0.18	0.49
5	13.80	30	27	7.15	7.35	0.08	0.27
5	6.50	90	17	34.50	35.38	0.34	0.86
5	9.52	90	42	15.00	14.95	0.64	2.97
5	13.80	90	32	7.95	7.93	0.09	0.31

Table 5. Ignition Time Statistics

GIRCFF Fabric No.	Irradiation W_o	Relative Humidity	Number of Tests	Ignition Time		Standard Deviation of Ignition	
				Single Shutter	Median	Mean	Time
				τ_i	$<\tau_i>$	σ_μ	σ
	W/cm^2	%	--	s		s	s
12	6.50	30	86	12.40	12.61	0.32	2.24
12	9.52	30	41	6.35	6.15	0.14	0.70
12	13.80	30	57	3.10	3.10	0.03	0.13
12	6.50	90	66	11.70	11.63	0.19	1.11
12	9.52	90	59	5.90	5.87	0.06	0.35
12	13.80	90	76	3.10	3.07	0.09	0.63

Table 6. Ignition Time Statistics

GIRCFF Fabric No.	Irradiation W_o	Relative Humidity	Number of Tests	Ignition Time		Standard Deviation of Ignition	
				Single Shutter	Median	Mean	Time
				τ_i	$\langle\tau_i\rangle$	σ_μ	σ
	W/cm^2	%	--	s		s	s
10	7.55	30	28	56.00	55.87	3.45	14.38
10	9.52	30	157	22.00	22.56	0.41	3.98
10	13.80	30	44	7.75	7.79	0.19	0.96
10	7.55	90					
10	9.52	90	27	26.50	26.42	0.46	1.83
10	13.80	90	26	8.50	8.42	0.11	0.40

of the analysis. They are the median ignition time and the estimates of the standard deviations of the median ignition time and of the ignition time itself.

Figures 4 and 5 depict the ignition probability of two of the tested fabrics as function of exposure time and heating intensity at 30% relative humidity. Figure 6 illustrates the influence of the relative humidity on the fabric ignition probability at two different levels of heating intensity for the third fabric.

Conclusions

The evaluation of the data obtained in ignition time frequency measurements produced the following conclusions:

(i) The median ignition time for all fabrics tend to decrease with increasing the heating intensity.

(ii) The median ignition time obtained differed no more than 3.15% from the previously obtained single shutter ignition time measurements.

(iii) The standard deviation of the mean ignition time and the standard deviation of ignition time tend to decrease with increasing heating intensity at 30% relative humidity. For 90% moisture content there exists the same tendency, although there are some discrepancies possibly due to the lack of resolution.

(iv) The 95% confidence interval for the mean ignition time is $\pm 5.0\%$ at most at 30% relative humidity and

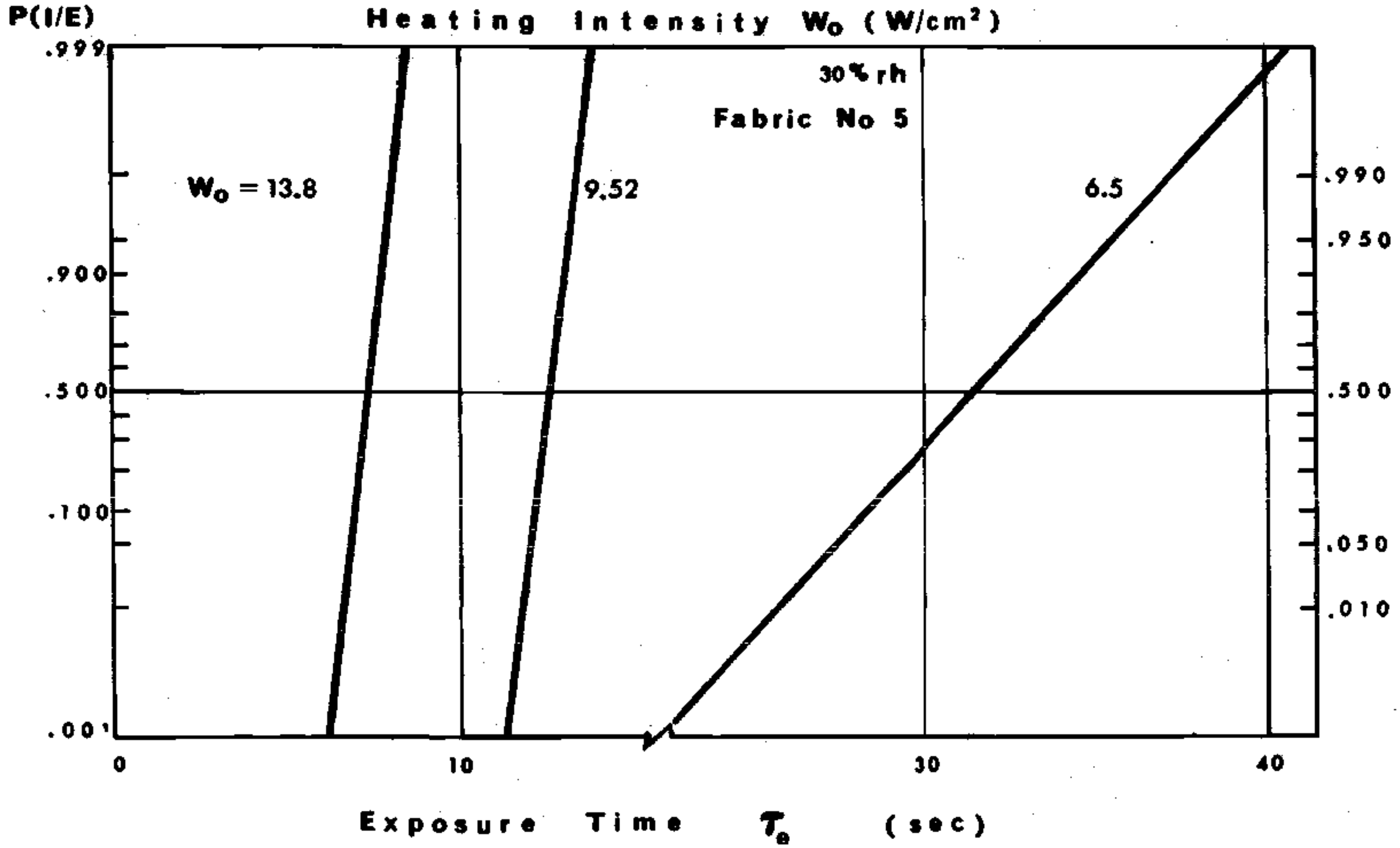

Figure 4. Ignition Probability for GIRCFF Fabric No. 5

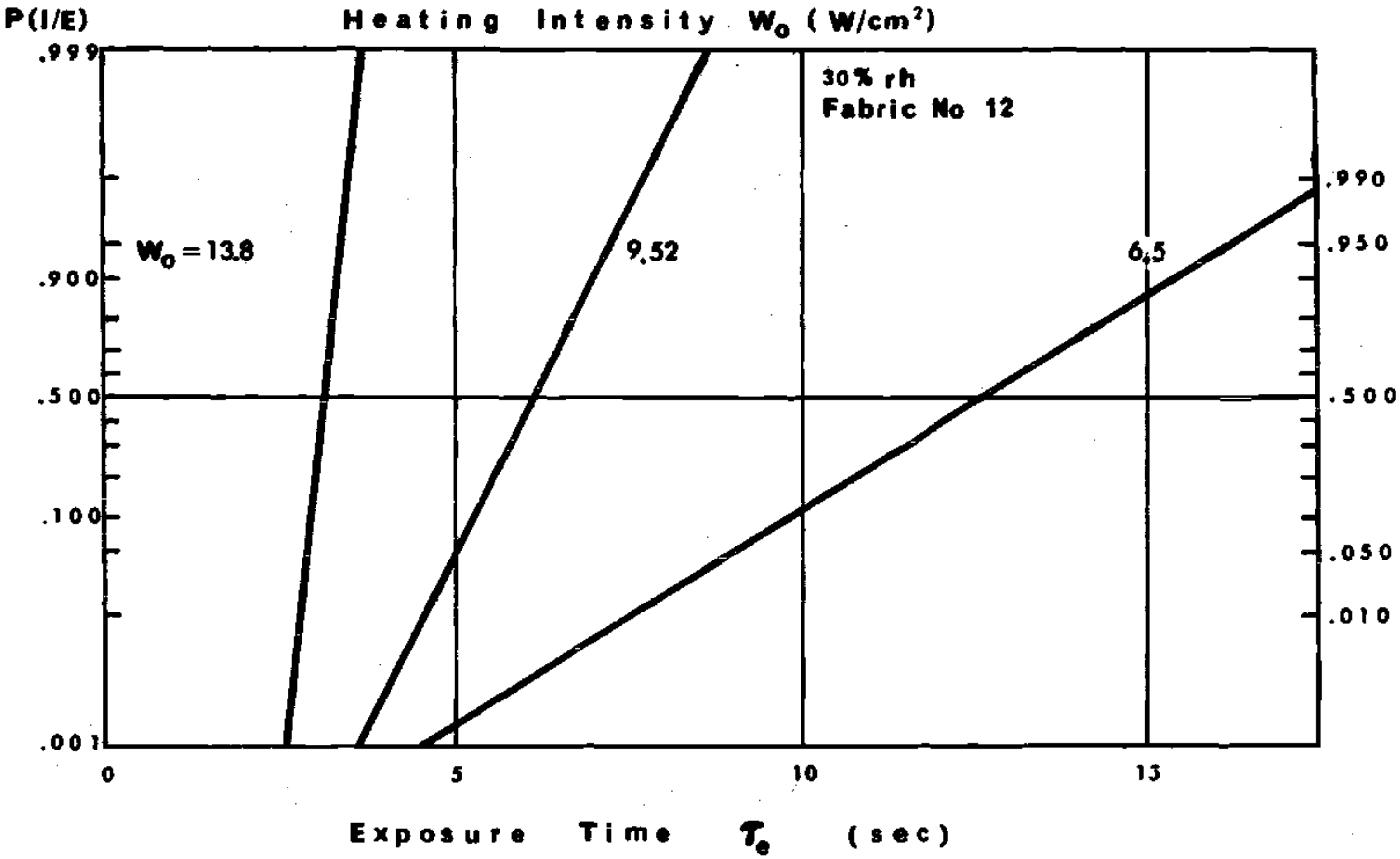

Figure 5. Ignition Probability for GIRCFF Fabric No. 12

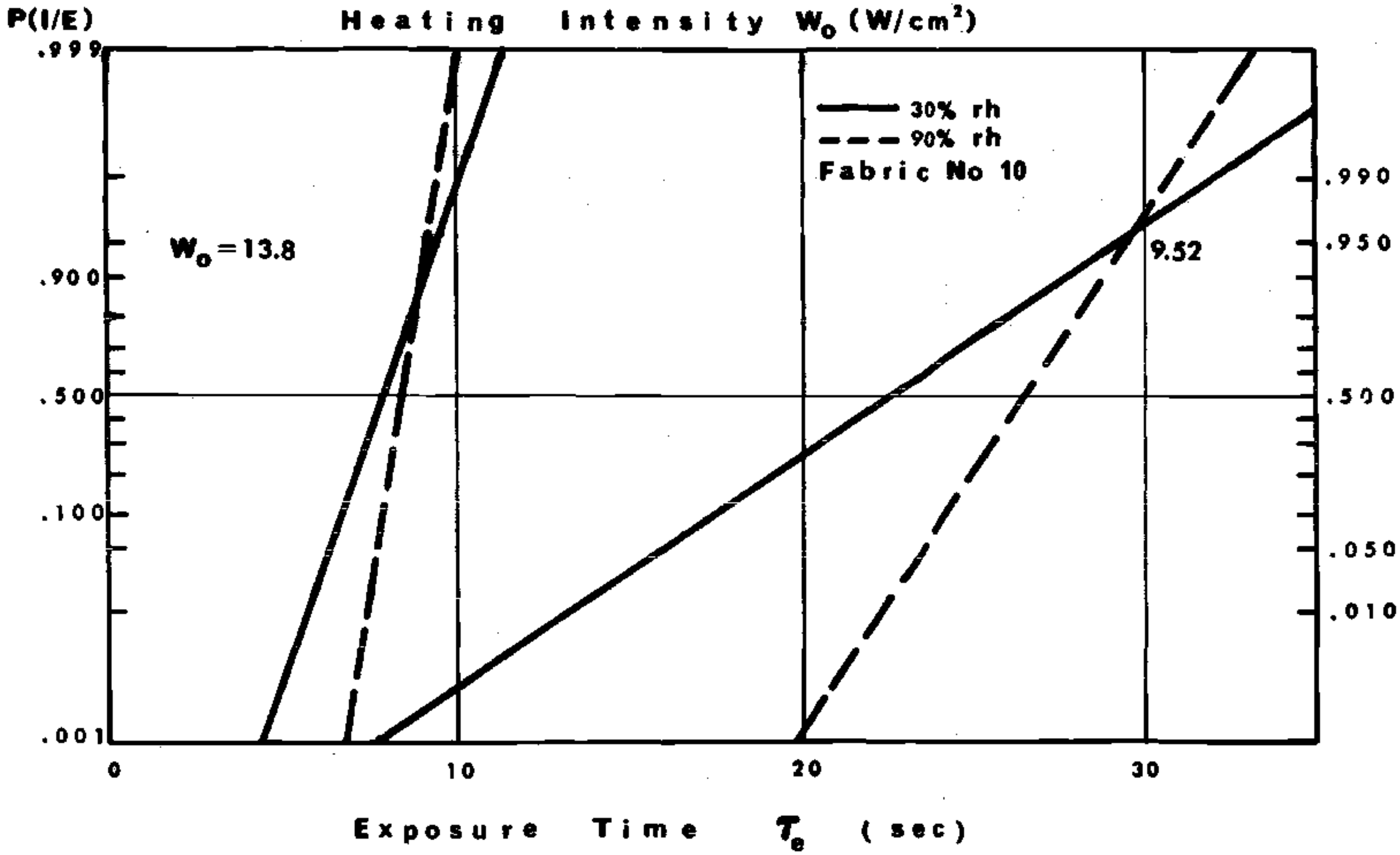

Figure 6. Ignition Probability for GIRCFF Fabric No. 10

$\pm 8.4\%$ at most at 90% relative humidity.

(v) For the cotton fabrics the median ignition time at a given heating level increases as the moisture content increases. It is necessary to supply energy for an additional period of time to eliminate the moisture. The nylon fabric shows the reverse behavior. The moisture content has no great significance on the ignition of nylon fabrics [32].

(vi) The 95.5% confidence interval of the ignition time tends to decrease as the heating intensity goes up, at 30% r.h., because the convective cooling plays a lesser role for high heating levels and it is largely responsible for the stochastic fabric response.

CHAPTER VI

PROBABILITY OF LABORATORY EXPOSURE CONDITIONS TO EXIST IN GENERAL

Relation Between Laboratory and Actual Use

In Chapter V was demonstrated how the fabric ignition probability is obtained under well-defined laboratory conditions.

Laboratory exposure conditions are defined in terms of:

(i) environmental humidity level,

(ii) initial temperature,

(iii) incidence heat flux for radiative heating, or flame temperature and gas flow velocity for convective heating,

(iv) orientation and geometry,

(v) exposure time.

The range of exposure conditions covered the conditions normally found in households, factories, hotels, and hospitals in connection with garment-fire initiated accidents.

In accordance with the probability concepts discussed in Chapter IV, it is now necessary to determine the probability with which the laboratory conditions are encountered in actual use of a particular garment.

In this chapter are presented the exposure conditions which exist most frequently, specifically the heating mode and intensity. The relative frequency and duration of exposure and the ambient conditions are to be obtained from time studies.

Classification of Ignition Sources

The ignition sources can be classified in accordance with the three modes of heat transfer between fabric and ignition sources, namely, radiative, convective, or conductive, or as a combination of these.

The more frequently encountered ignition sources are kitchen ranges, open flames, matches, cigarette lighters, candles, and flammable cleaning fluids (see Table 3 in Chapter II).

As an example, an open fire as a barbecue, a candle, a cigarette lighter, can be considered to be a convective heat source; an electric kitchen range, an electrical hot plate, a space heater, can be regarded as a radiative source. However, if contact occurs between source and fabric as in accidents caused by cigarettes, conduction prevails over the other two modes and a radiactive source can become a conductive source.

Characterization of the Ignition Sources

In order to achieve a complete characterization of an ignition source one needs to evaluate the series of aspects discussed next.

Use Frequency

It is the probability with which an ignition source is actually employed. It is to be estimated from statistical data on marketing trends and from exposure time studies.

Exposure Frequency

It is the probability with which a certain exposure condition is actually found; that is, the fraction of time during which a given fabric is exposed to a given heating intensity and to under given ambient conditions. It is to be determined from exposure time studies for every ignition source.

Exposure Duration

It is the time during which a given exposure exists. Characteristic times of exposure are to be evaluated for every ignition source through exposure time studies.

Ambient Condition Frequency

The relative frequency with which given relative humidity level and initial temperature are actually found is to be determined from climatological data and studies on space conditioning.

Heating Intensities

It is expected that every ignition source in its active condition shows a wide range of heating intensities in its immediate vicinity.

Radiative thermal interaction between the heat source and the heat receiving material is characterized by the irradiation from the source and by the optical material properties. To define the source one needs to find the net radiant incident power flux on the receiver material and its spectral energy distribution, however, this last parameter is not important for nonmilitary ignition sources, that is, for prevailing infrared radiation.

Convective ignition sources, such as gas flames, are quantitatively defined by the gas temperature and the convective film coefficient.

Conductive ignition sources are characterized by their surface temperature and the material properties, namely, conductivity, density and specific heat. Most contact ignition sources are made of metals whose properties are known, and consequently the knowledge of the surface temperature is sufficient to characterize the conductive sources.

In this work, we found the spatial heat flux and temperature distribution for several common ignition sources. We worked with kitchen ranges because they are representative of all thermal interaction processes. Also, we analyzed cigarette lighters, matches and candles.

Only convective and radiactive sources were considered. Conductive sources are out of the scope of this study. Ignition of fabrics by conduction is less frequent than other modes of thermal interaction. We did not consider flammable liquids either.

Axial symmetry of ignition source was assumed, even though it is known that symmetry is not always guaranteed for kitchen ranges. Only small fluctuations were expected from gas ranges.

Measurements of Heating Intensities

Ignition Source Scanning Apparatus

A portable scanning device (ISSA) was designed and built to carry total heat flux and temperature sensors, and a linear variable differential transformer. Those sensors and the linear transducer permit to establish spatial heat flux and temperature distribution in the immediate neighborhood of potential ignition sources. Figure 7 shows the general overview of the set-up: the scanning apparatus, the ignition source, and the ancillary instrumentation.

The apparatus was designed to comply with the following requirements:

(i) Light weight; current and future off-campus measurements can be undertaken with ease.

(ii) Provision for a continuous traversing motion for mapping a continuous pattern of the heat flux and temperature in one direction.

(iii) Adjustment for discrete displacements in two directions perpendicular to the traversing motion.

(iv) Ability to be tilted to any angular position.

A supporting table structure was constructed to hold

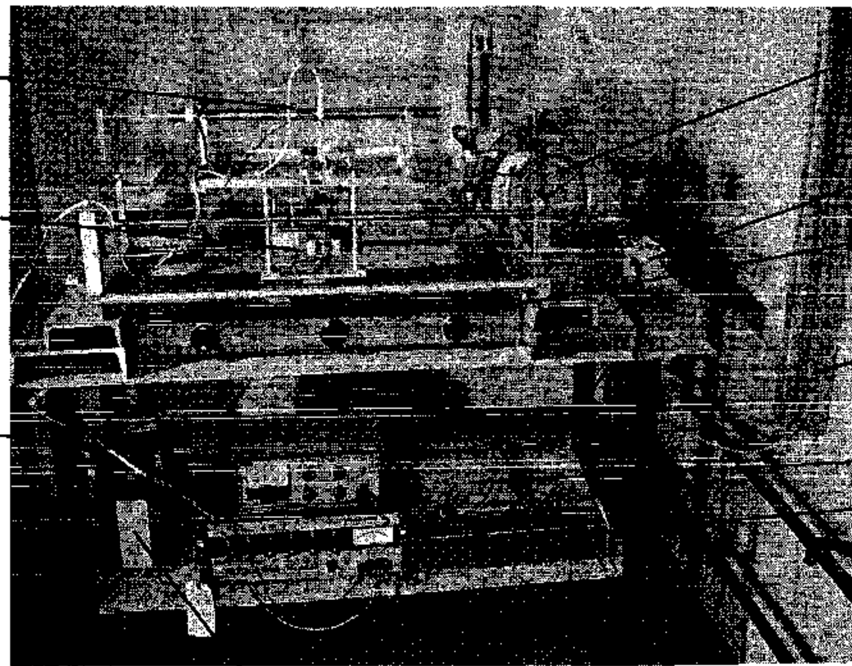

Figure 7. Overview of the Experimental Arrangement for Heating Intensity Measurements

the apparatus, the ignition source, and the necessary instrumentation. It was made of angle iron 2" x 1/8" with a base plate of transite 1/2" thick. Aluminum and steel U-channels were used to supply an ample range of vertical levels, from zero to seven inches, between the heat sink and the sensors.

The apparatus basically consists of the following major components:

(i) a sensor holder unit,

(ii) a conveying system, and

(iii) a main frame.

Figures 8, 9, and 10 show the general assembly of the apparatus. The main frame was designed such that it may be set over most of the commercially sold kitchen electric and gas ranges. It has 30-inch span and a 10-inch net clearance to scan burners, coils, etc. Most of the apparatus was made of aluminum to guarantee a light weight at low cost.

The conveying system can be, in turn, subdivided into three major parts as follows:

(a) An upper frame. It serves as a base for the linear transducer and has a double action clamp to hold the sensor holder unit in any vertical, lateral and angular psoition. An inconel shield is placed right under the frame to protect the linear transducer against intense radiation.

(b) The drive mechanism. It consists of two parallel shafts, 10-1/2 inches apart. One is a steel threaded rod,

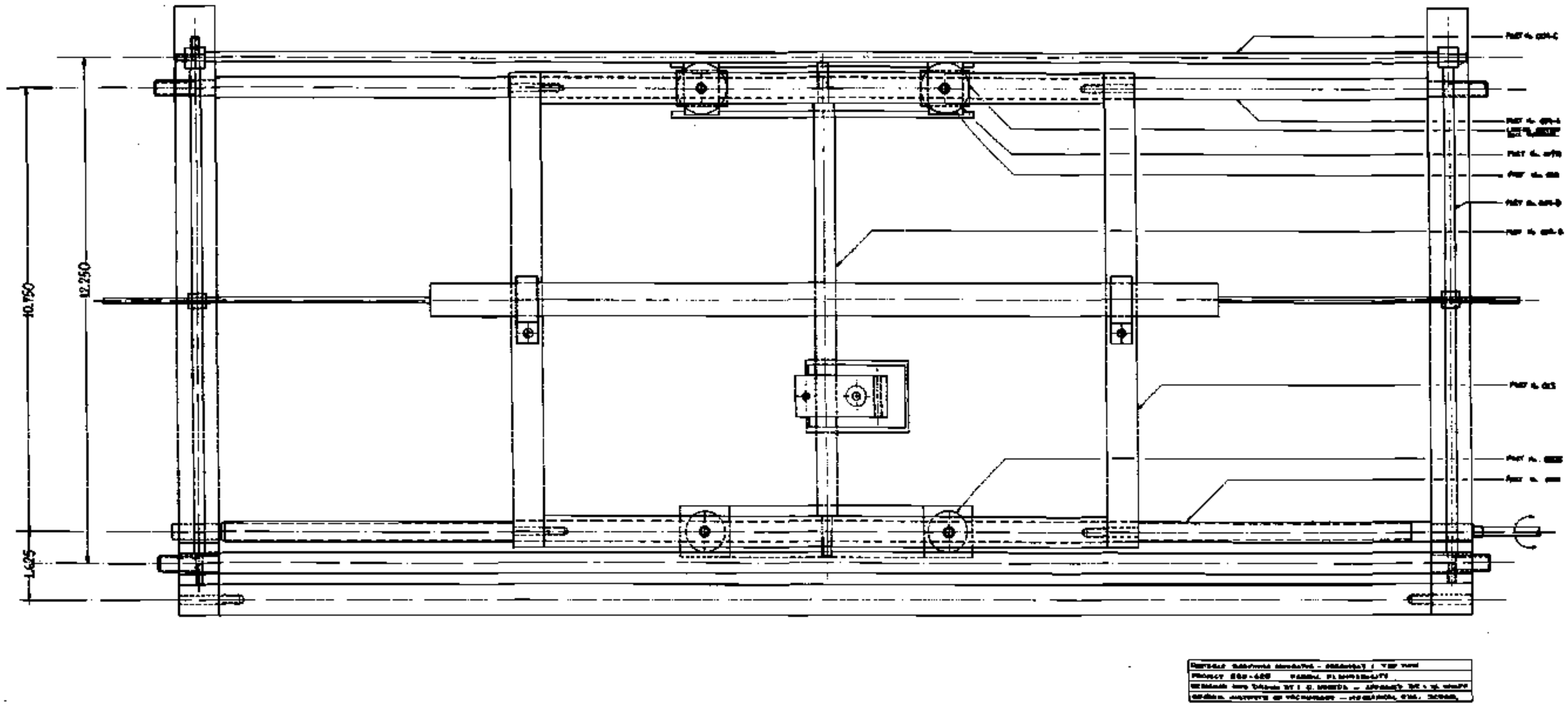

Figure 8. Ignition Source Scanning Apparatus Assembly: Top View

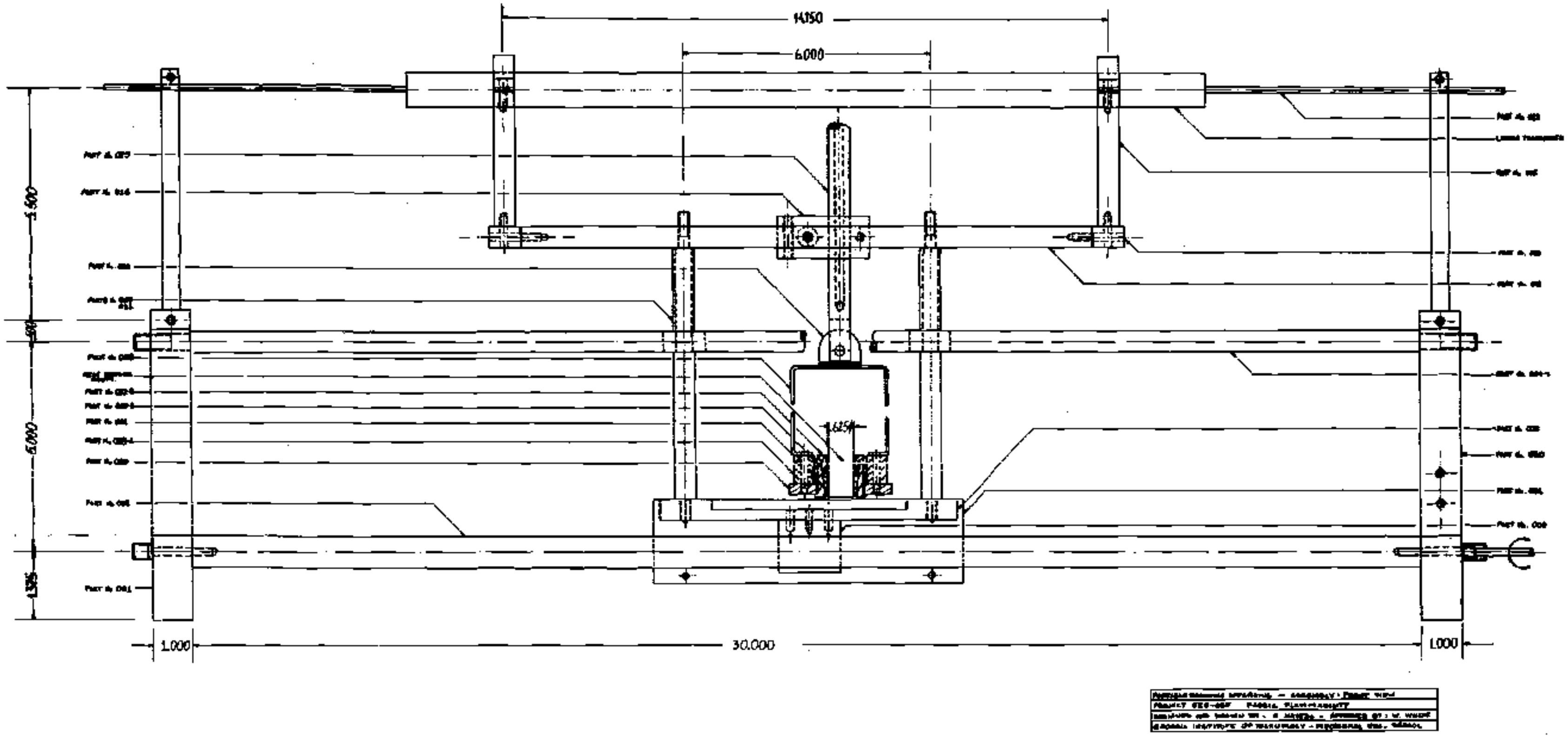

Figure 9. Ignition Source Scanning Apparatus Assembly: Front View

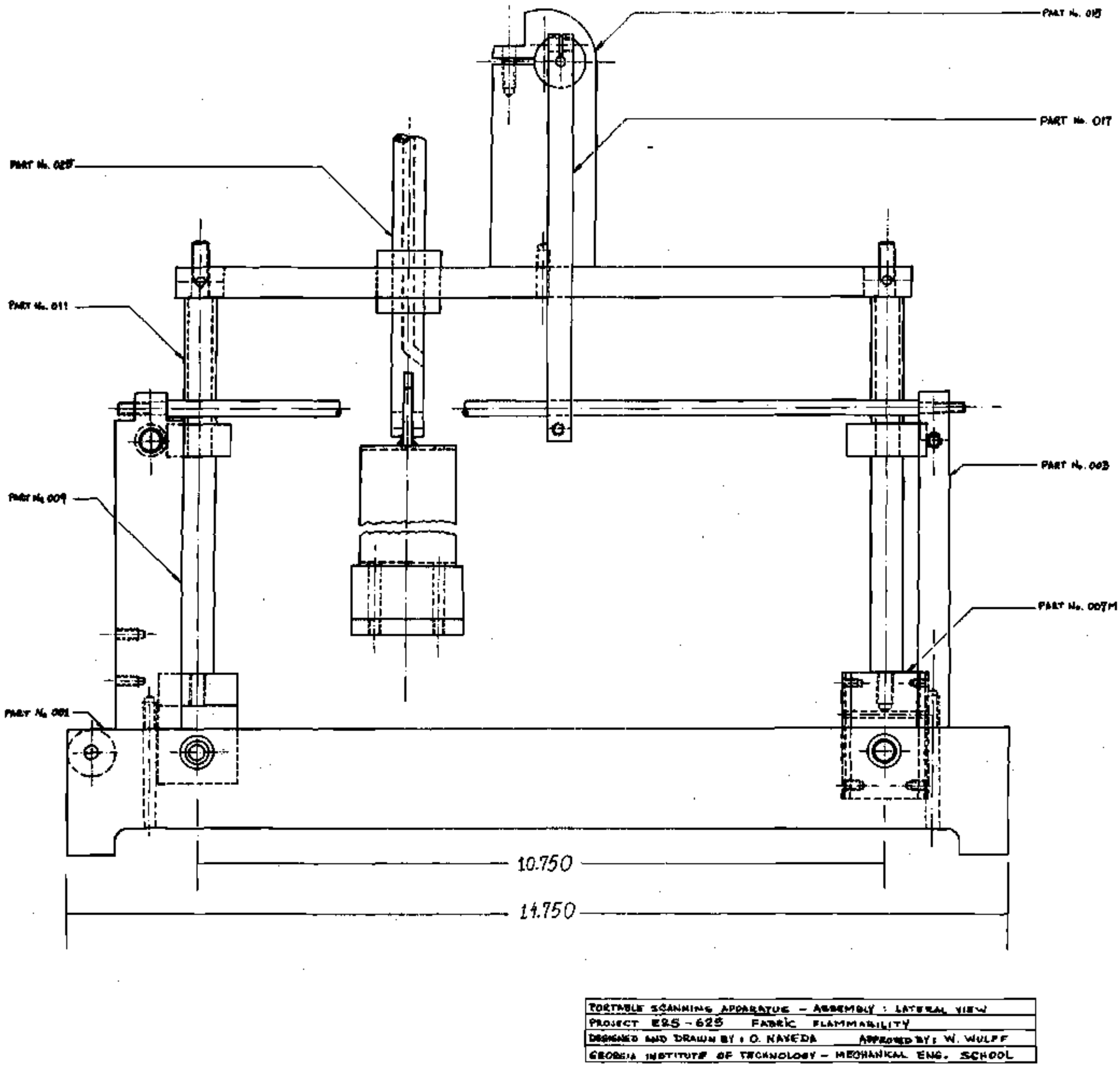

Figure 10. Ignition Source Scanning Apparatus Assembly: Lateral View

having 1/2-inch diameter and 13 threads/inch, which acts as a lead screw and is driven by a Bodine Motor Model 102 with voltage regulator, manufactured by Talboys Engineering Corp. The second shaft is a case hardened and ground rod, 1/2-inch diameter, by Thompson Industries. Linear motion ball bushings provide smoothness of motion.

(c) Connecting Columns. Four aluminum rods join the upper frame and the drive mechanism.

The sensor holder unit is a female conically shaped brass receiver in which is clamped the heat flux sensor, and kept in a fixed position by means of the threaded brass screw. A conically shaped split sleeve of transite, an insulator, is located between the heat sensor and the receiver to prevent any damage to the sensor due to heat conduction. The sensor receiver is silver soldered to a rectangular steel plate, the receiver base, on which rest a 1/16-inch thick steel flame shield. This shield is separated from the base by two blocks of transite and engages with a rod which goes through the double clamp of the upper frame.

The temperature sensor is held into position and moved up and down to any vertical position by means of a clamp adaptor which is rigidly coupled to the vertical adjusting rod.

A second inconel shield is attached to the receiver's base for protecting the heat sensor's electrical cable.

Ignition Sources

The kitchen gas range analyzed in the laboratory is a three-burner Kenmore gas hot plate Model No. 119.15031. Its dimensions are 29.1/8" long, 10.5/8" wide, and 4.5/6" high. The fuel is natural gas. The diameter of the ring of holes from which gas-air mixture emerges is 2.15 inches. The flame, at fully opened valve, is around 4 inches in diameter and approximately 2 inches high.

The kitchen gas range studied in a conventional kitchen is a Sears Kenmore, Series 71731 oven. One of the two big burners was studied. The ring of holes has a diameter of 3.25 inches. At fully opened valve the flame dimensions were as in the laboratory.

The electric range is represented by a single, on-off controlled, free glowing coil, 115 volts, 800 watts hot plate. The external diameter of the coil embedded in a ceramic base is 6 inches.

The second kitchen electric range studied is a built-in Westinghouse, four burner, oven and broiler combination. It has one burner of 2.6 kW and three burners of 1.6 kW. The big burner was studied.

The set of small sources studied were household matches and candles, and a dispoz-a-lite cigarette lighter.

Ancillary Instrumentation

The total heat flux measurements are achieved by means of a HY-CAL asymptotic water-cooled calorimeter Model No.

C-1301-A-60. This sensor is self-generating and of fast response. The working capacity is 60 Btu/ft^2 sec and its absorptivity is 0.89.

A Linear Voltage Differential Transformer (LVDT), Model 5000 HR-DC, manufactured by Schaevitz Engineering Co., is used to position the heat flux sensor with respect to a fixed reference such as the center of the burner or coil. This linear transducer needs an input of 24 volts D.C. and gives an output of ± 5 volts at full displacement. It possesses an infinite resolution and a very high repeatability.

The external power required for the linear transducer is taken from a Heathkit Regulated Linear Voltage Power Supply, Model IP-27.

The signals corresponding to heating intensity and position are recorded on a X-Y Plotter. This plotter is a Hewlett-Packard 7005B X-Y Recorder.

Because of the smallness of the signal emitted by the heat sensor and plotted in the recorder, a Hewlett Packard Differential Voltmeter is used as a DC Amplifier. The gain amplitude-ratio was 1,000 or 60 decibels. The DV meter used is a Hewlett Packard 3420 B Volt-Ratio Meter.

The temperature measurements are achieved in two different ways:

(i) For convective sources, a chromel-alumel thermocouple is used. The cold junction is an Omega Ice-Point Cell.

(ii) For radiative sources, the surface temperature is averaged arithmetically from individual temperature measurements accomplished by using a Pyro Micro-Optical Pyrometer, Model No. 95, capable to measure temperatures in the range of 700°C-3200°C.

Additional instrumentation is needed for the characterization of the kitchen gas range in the laboratory. A U-tube, filled with water, is used to get the supply pressure in the natural gas pipe line. The pressure measurements are taken downstream of the flowmeter. The flow rates of natural gas consumed by the gas hot plate are determined by means of a positive displacement "Precision" Wet Test Meter, manufactured by Precision Scientific Co. The hourly rate is obtained by one minute observations.

For calibration purposes, a Millivolt Potentiometer by Leeds & Northrup, Catalog No. 8686 and a Simpson meter 250 were utilized.

Figures 11 and 12 show the schematic of instrumentation required for the heat flux and for temperature measurements, respectively, while Figure 13 depicts the optional instrumentation necessary for the kitchen gas range.

Experimental Procedure and Data Reduction

The sensors and recorders are calibrated as explained in Appendix C.

A coordinate system was chosen in the geometrical center of the heat-producing element of the heat source.

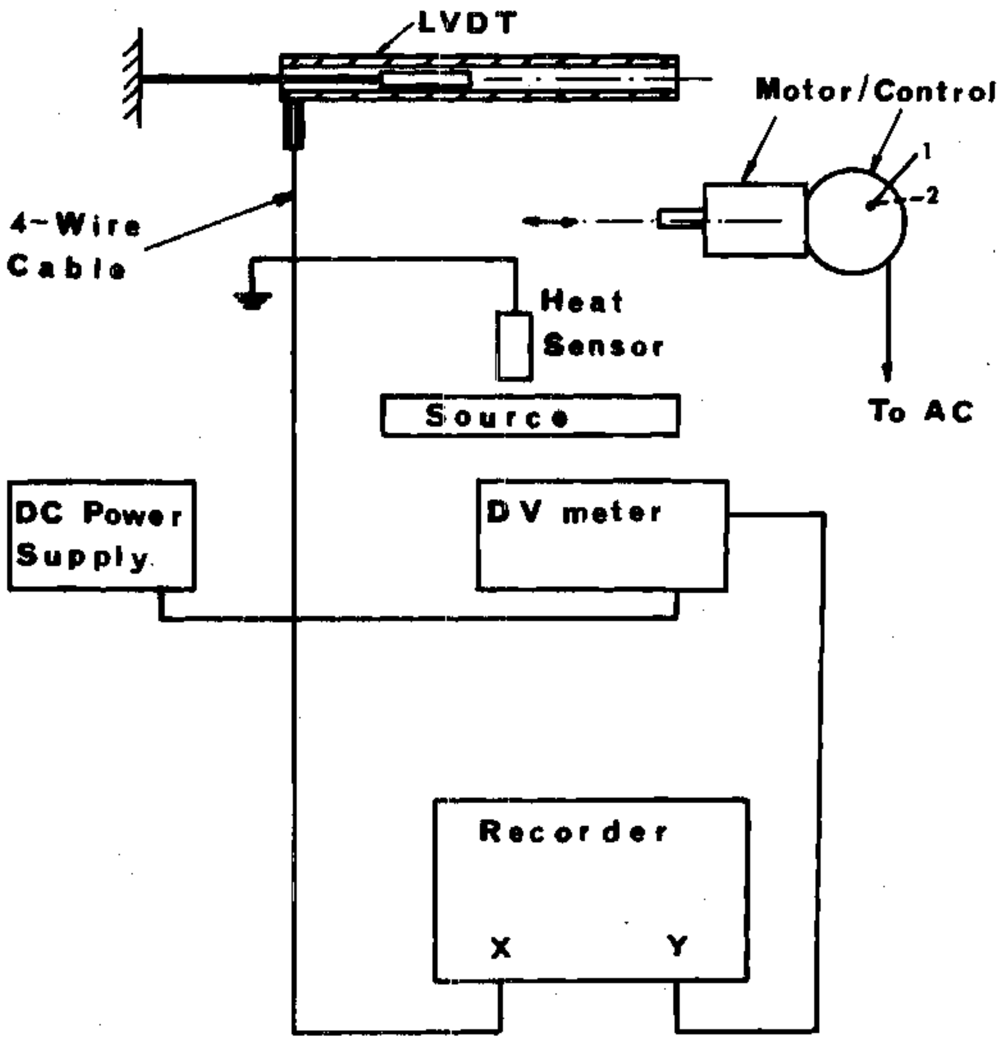

Figure 11. Schematic of Instrumentation for Heat Flux Measurements

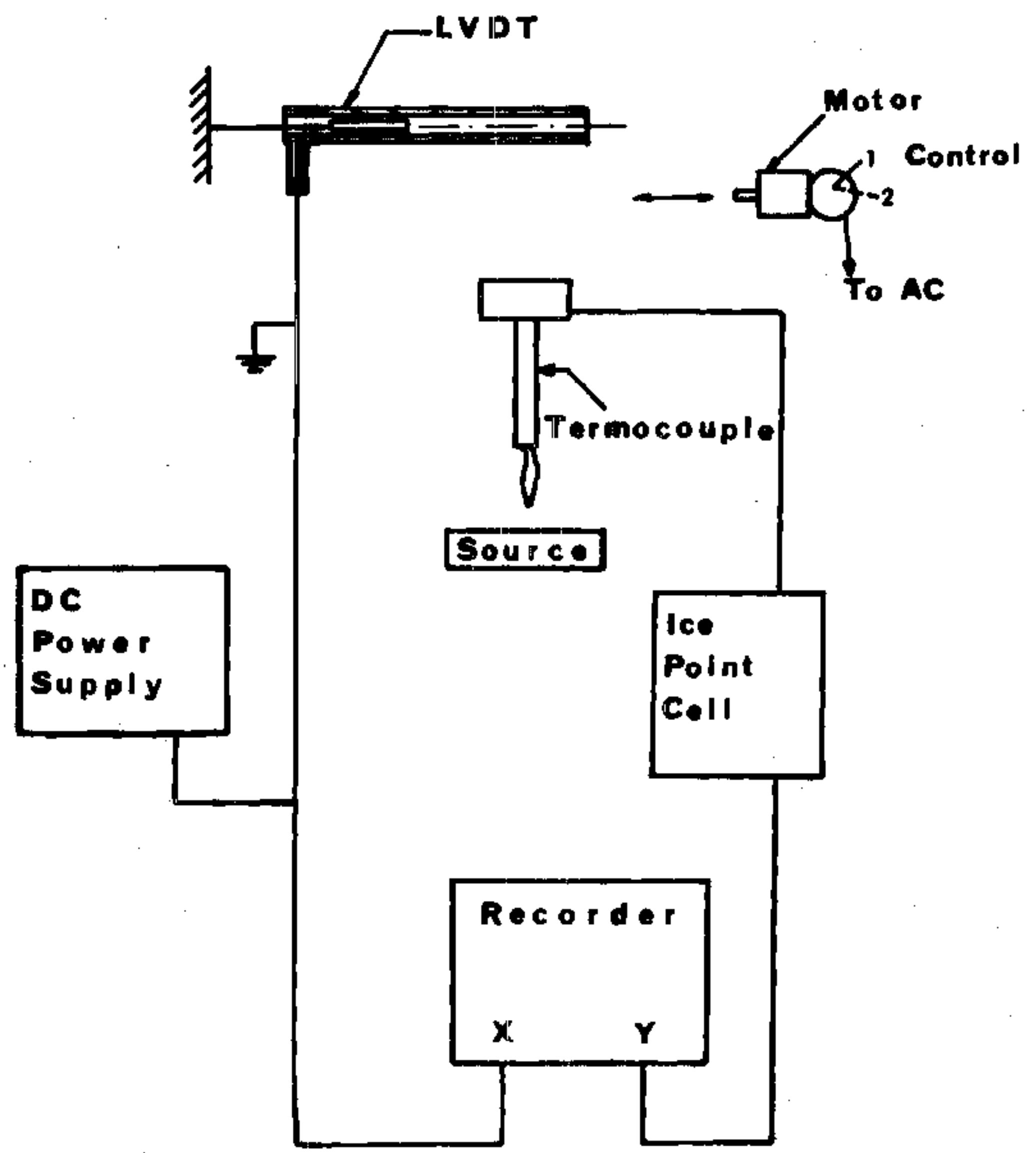

Figure 12. Schematic of Instrumentation for Temperature Measurements

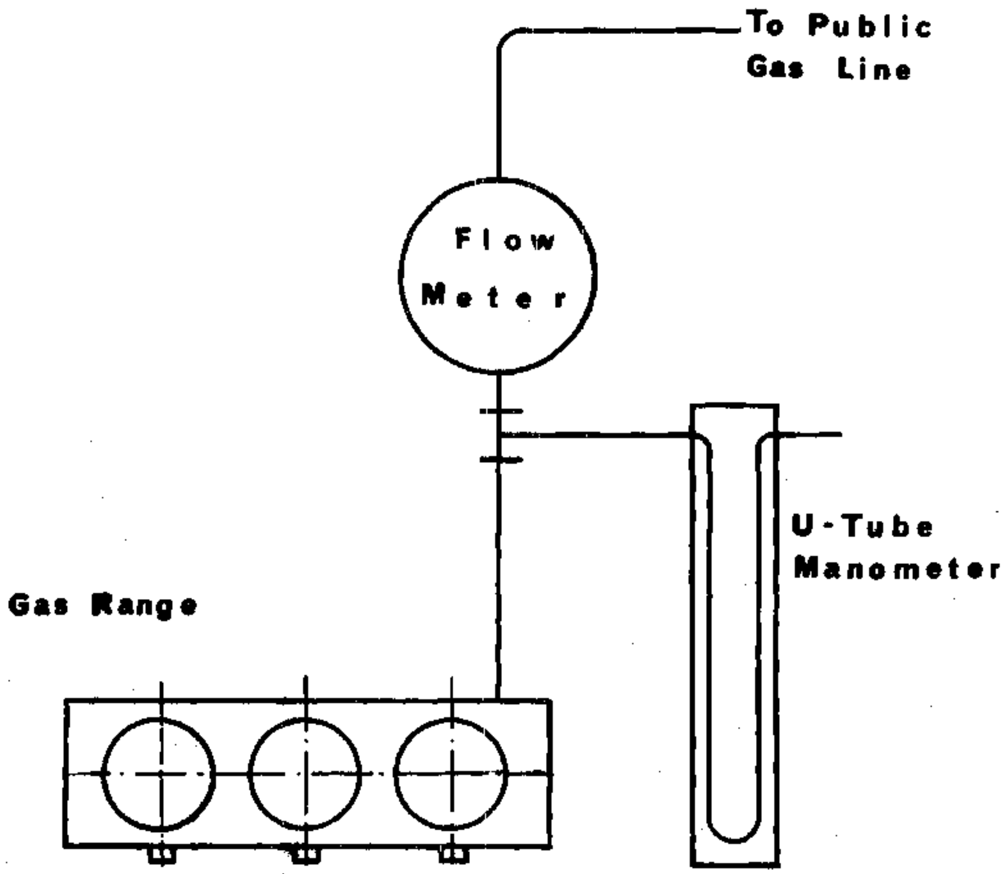

Figure 13. Schematic of Fuel Flow Rate and Supply Pressure Measurements, Gas Range

The coordinate system is depicted in Figure 14 below. The Y-ordinate corresponds to the continuous traversing direction of the apparatus, the Z-ordinate is the lateral displacement, and the X-ordinate measures the vertical position with respect to burner or coil top.

Heat flux and temperature measurements were always taken with the utensil support grid in place. Measurements were also carried out with a sauce pan placed on the grid. Figure 15 shows the configuration of pan and burner.

Heat flux and temperature are measured as follows:

(i) The heat flux or temperature sensor is positioned at specific X and Z positions, using the double action clamp of the conveying system, such that the normal to the heat flux sensor surface is parallel to the flame axis or perpendicular to the support grid plane.

(ii) The ignition source is turned on fully and allowed to reach thermal equilibrium during at least three minutes.

(iii) The sensor holder unit is then passed over the entire length of the heat element.

The results are the graphs of power flux or temperature as a function of Y-position, at given X and Z, that is $Wo(y)_{x,z}$ or $T(y)_{x,z}$.

The heat flux sensor was also positioned at angles of 30°, 45°, 60° with respect to the vertical heat source axis.

A continuous pattern of heat flux intensity versus

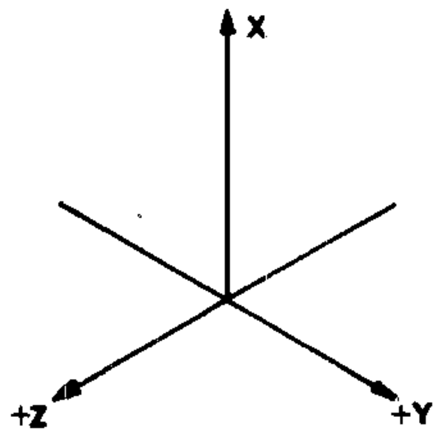

Figure 14. Coordinate System for Heat Flux and Temperature Measurement

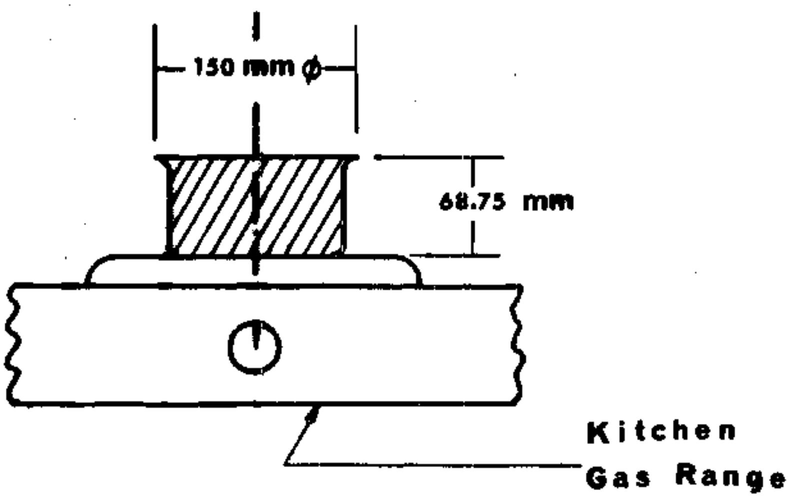

Figure 15. Configuration of Burner Covered by Cooking Utensil

position has been recorded for the position with 90° between the normals of sensor and the burner.

The data taken in rectangular coordinates is averaged and transformed to polar coordinates. The spatial distribution of heat flux and temperature is completely represented by one quarter of any half plane through the vertical axis.

The transformation is accomplished by using the following equations:

$$r = (x^2 + y^2 + z^2)^{1/2} \tag{6.1}$$

and

$$\phi = \tan^{-1} \frac{X}{(y^2 + z^2)^{1/2}} \tag{6.2}$$

and the results are presented as lines of constant heat flux or temperature.

Results

The results obtained from the measurements of heating intensity and temperature on kitchen ranges can be summarized as follows:

(i) The diffusion flame of the kitchen gas range showed a wide band of fluctuation in the heat flux and temperature patterns. Figures 16 through 19 present some results for the laboratory kitchen gas range.

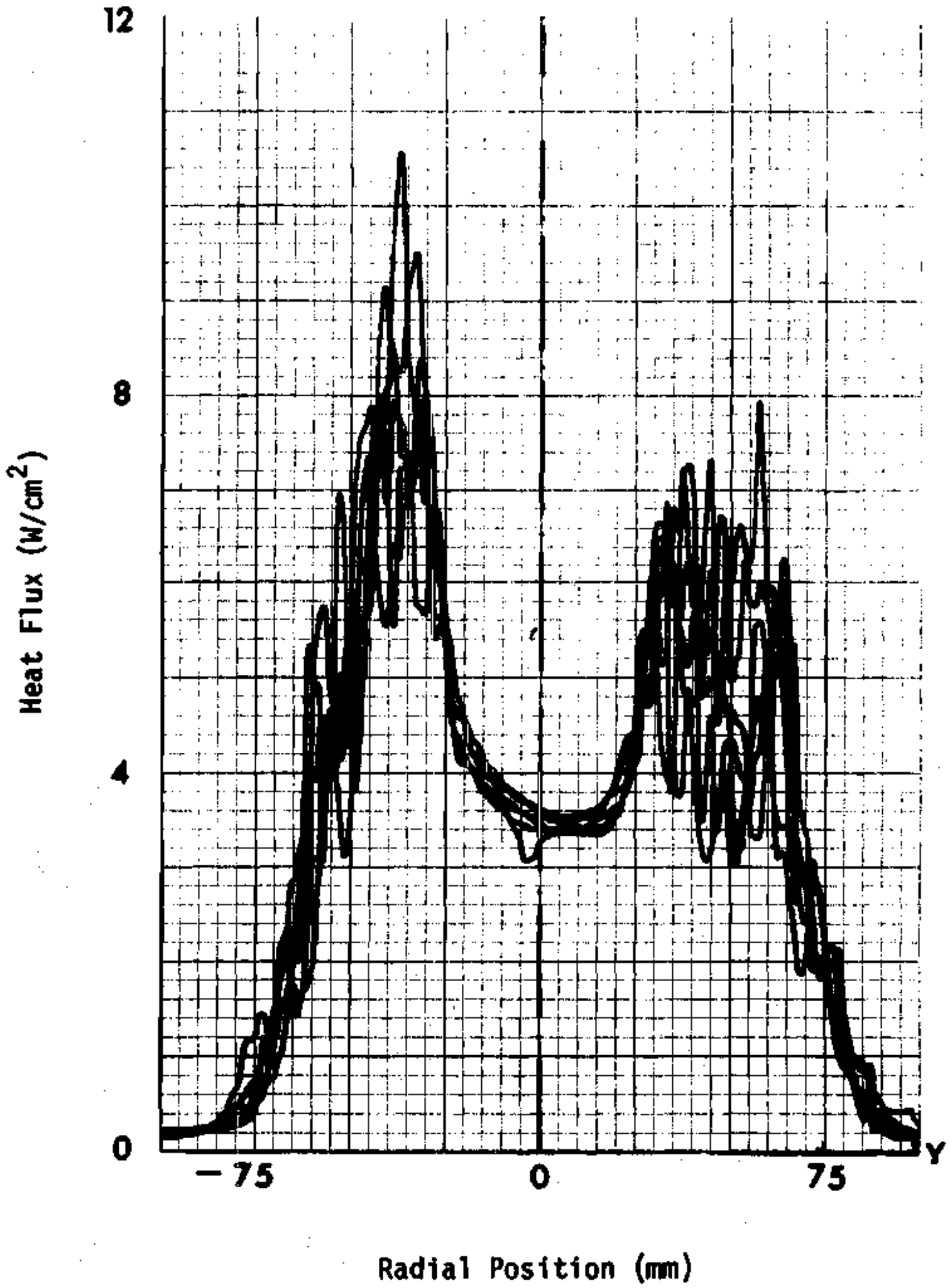

Figure 16. Heat Flux Distribution
At X = 25 mm above Burner Top,
in the Vertical Center Plane.
Kenmore Gas Hot Plate, Model No.
119.15031.

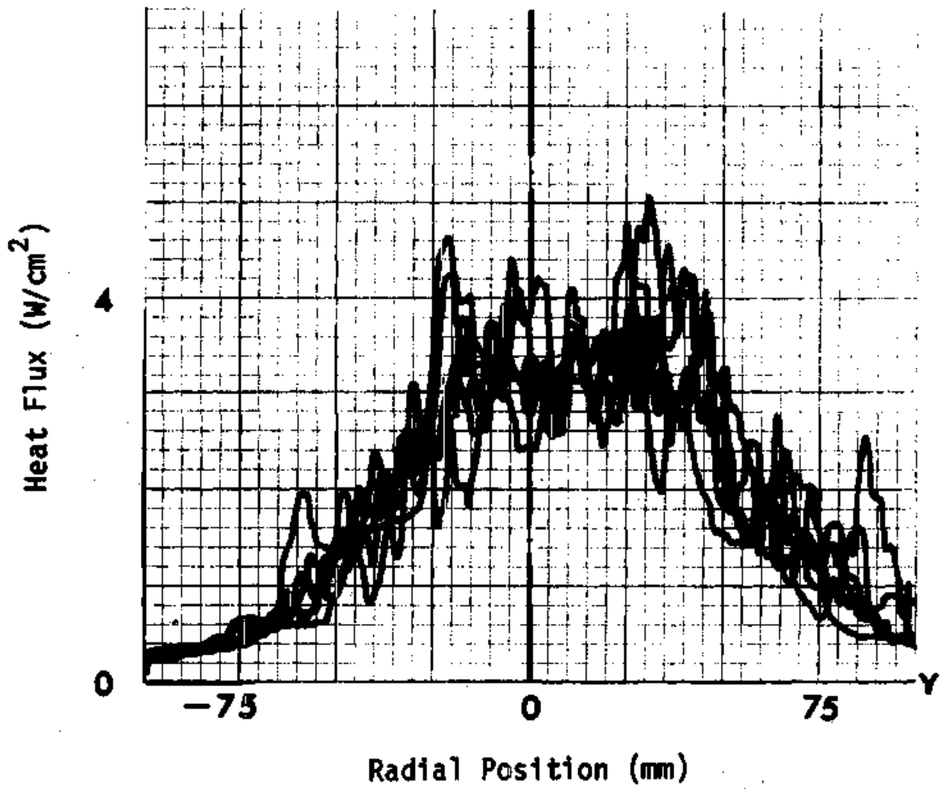

Figure 17. Heat Flux Distribution
At X = 75 mm above Burner Top, in the Vertical Center Plane. Kenmore Gas Hot Plate, Model No. 119.15031.

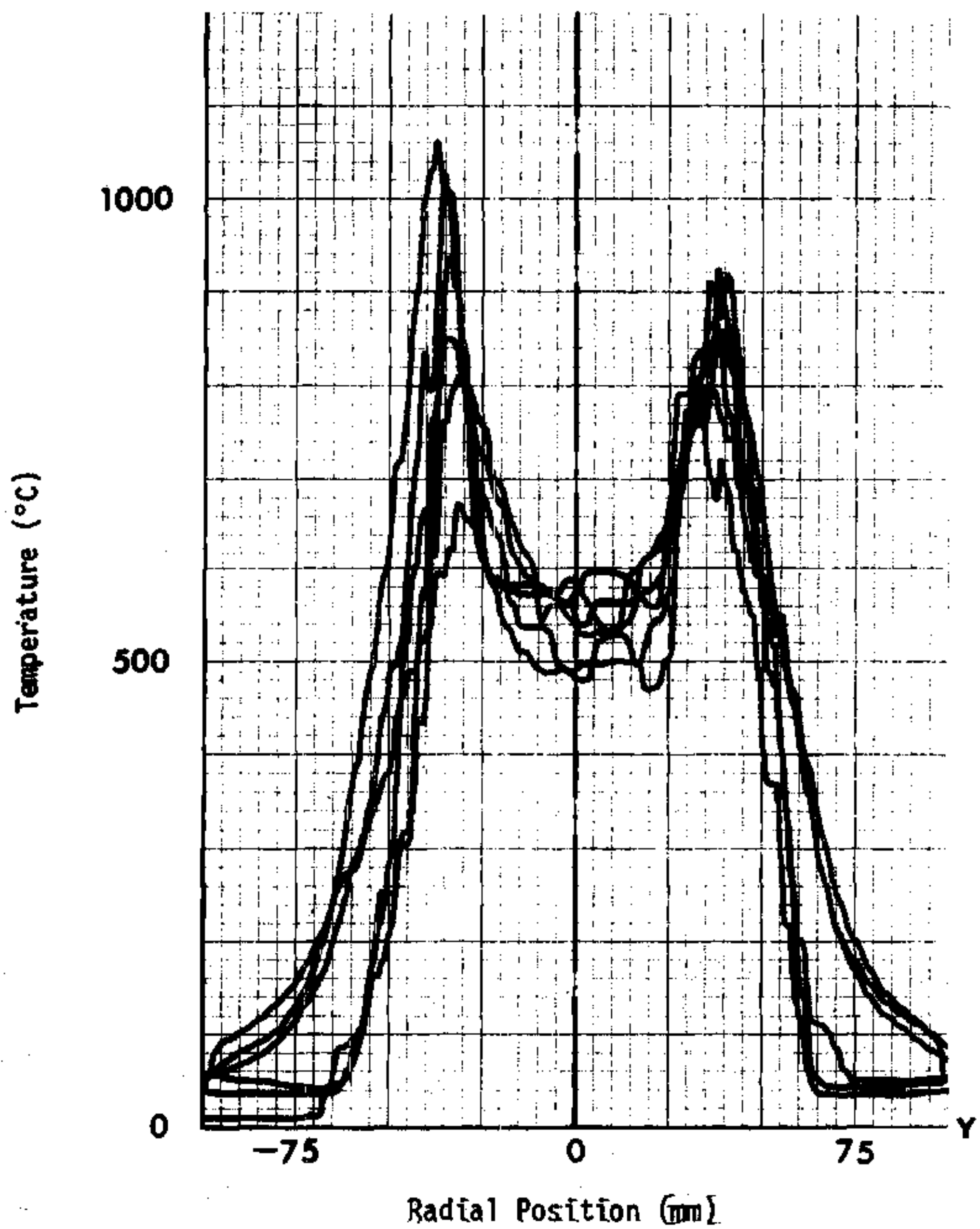

Figure 18. Temperature Distribution At X = 25 mm above Burner Top, in the Vertical Center Plane. Kenmore Gas Hot Plate, Model No. 119.15031.

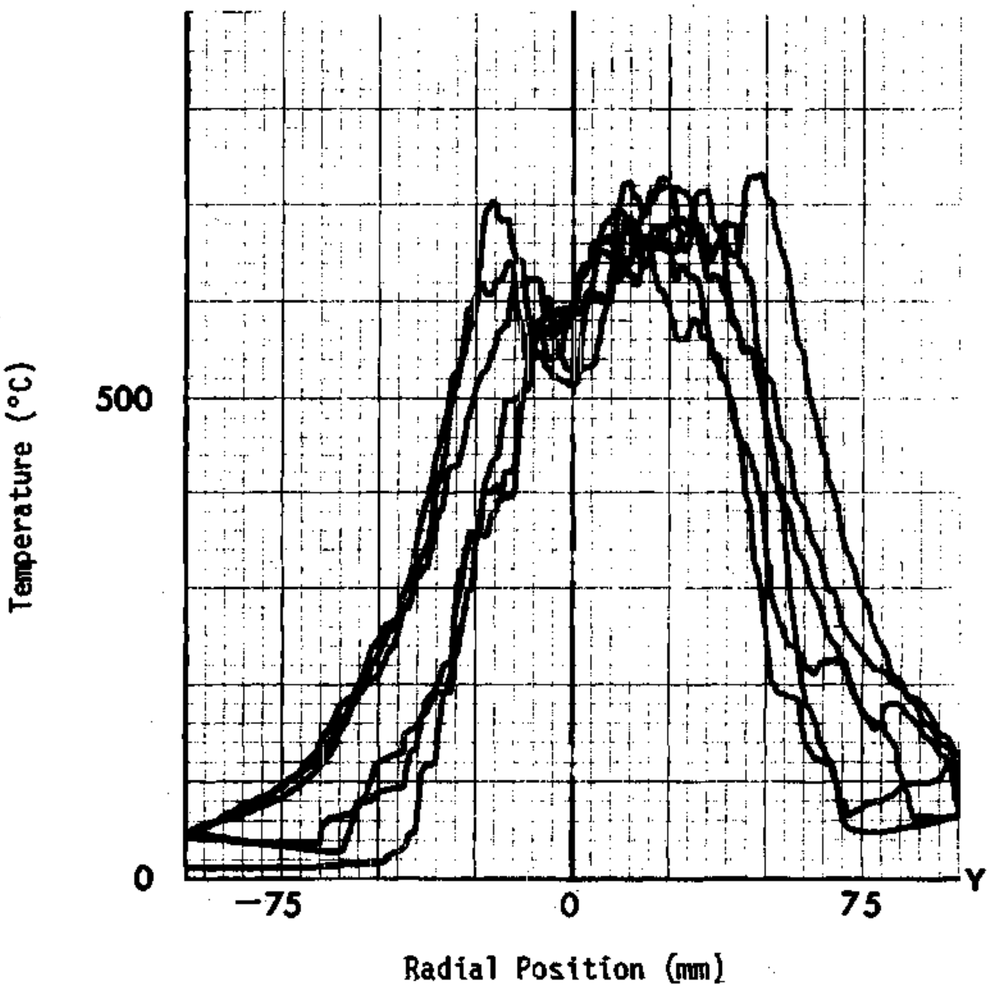

Figure 19. Temperature Distribution At X = 50 mm above Burner Top, in the Vertical Center Plane. Kenmore Gas Hot Plate, Model No. 119.15031.

(ii) The electrical range showed less temporal fluctuation in heat flux than the gas range, as depicted in Figures 20 and 21.

(iii) The depressions at the centerline are due to the physical appearance of the ignition sources, the grid in the case of the gas ranges and the central part for electrical ranges. This dip in radial heat flux and temperature distributions disappears at larger distances above the source.

(iv) The pattern peaks are lower for large distances from the heating elements in both vertical and lateral directions. Figures 22 through 26 illustrate that clearly.

(v) The influence of the right hand side burner on the center burner is shown in Figure 27. The presence of this right burner shifts the heat flux curve to the right by about 10% of the peak to peak distances.

(vi) The effect of cooking utensils, such as a sauce pan placed over the burner, is to deflect the heat flux outwards and to reduce its magnitude. Figure 28 shows the peripheral heat flux distribution of a covered gas flame, whereas Figure 29 illustrates the deflection of the heat flux by a sauce pan.

(vii) It was determined that the center plane suffices for obtaining the heat flux and the temperature distributions. Figures 30 through 35 show these distributions in polar diagram for all kitchen ranges studied. The dashed lines are best estimates.

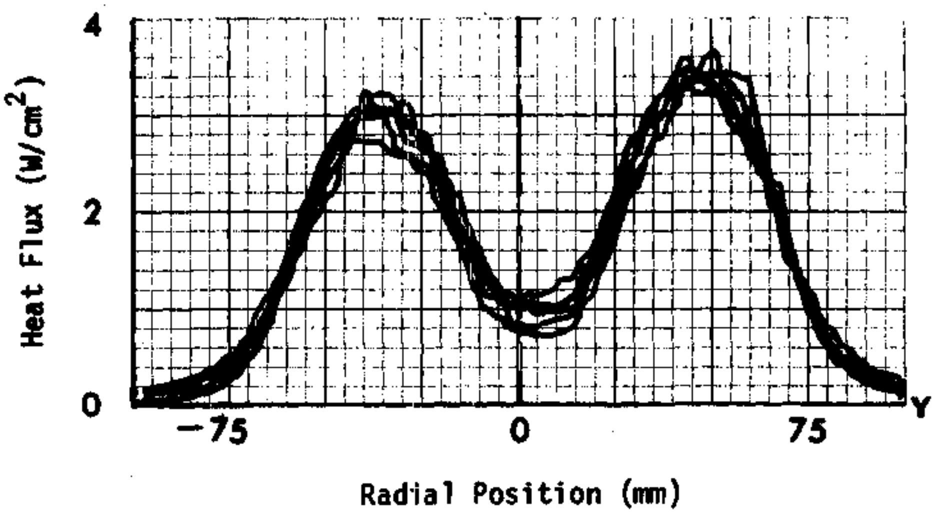

Figure 20. Heat Flux Distribution. At X = 12.5 mm above Ceramic Base Top, in the Vertical Center Plane. Open-Coil Hot Plate, 800 Watts.

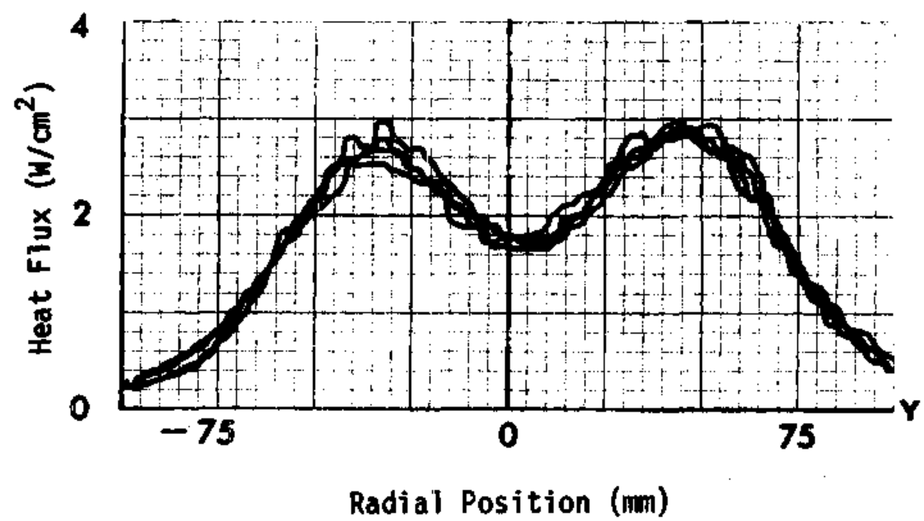

Figure 21. Heat Flux Distribution. At X = 25 mm above Ceramic Base Top, in the Vertical Center Plane. Open-Coil Hot Plate, 800 Watts.

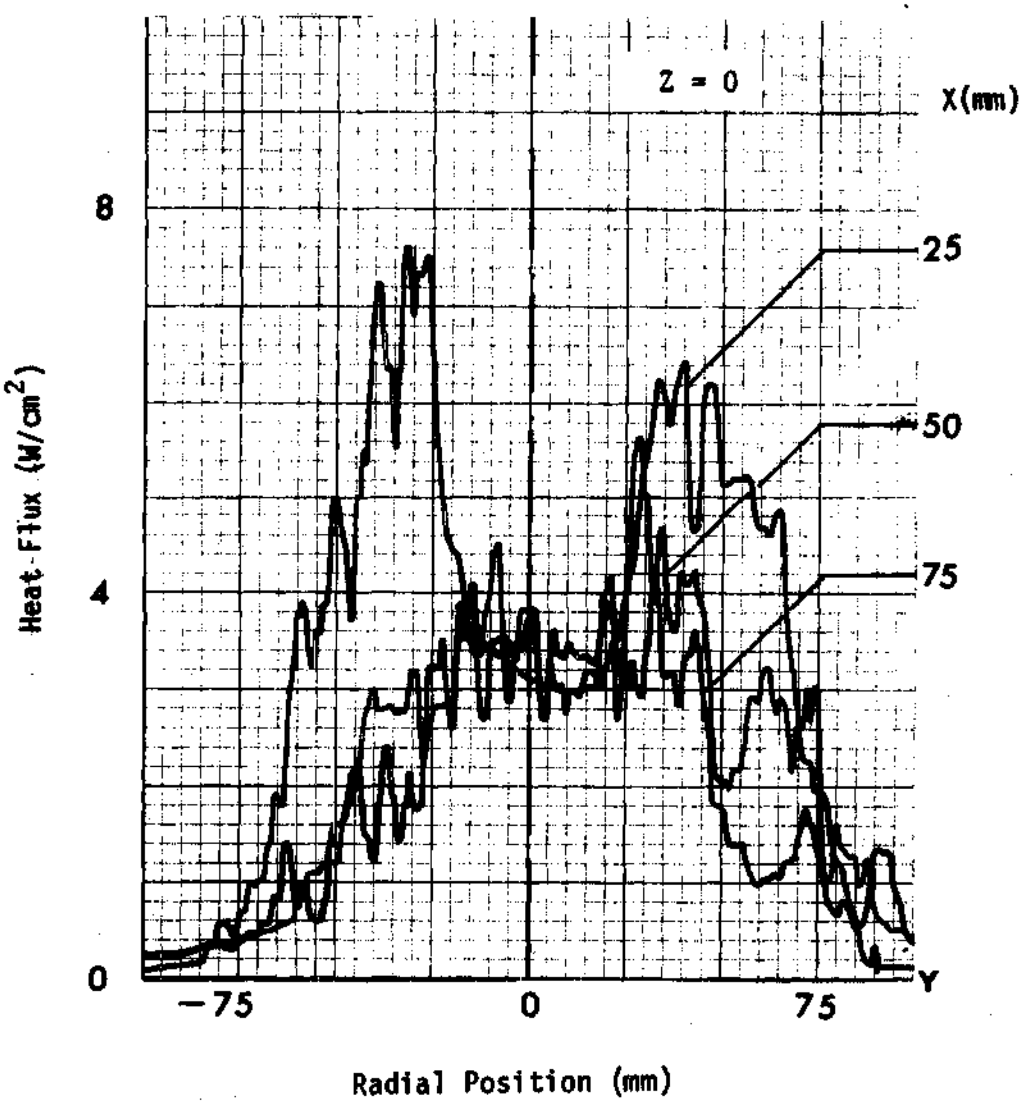

Figure 22. Height Effects on Heat Flux Distribution. In the Vertical Center Plane. Kenmore Gas Hot Plate, Model No. 119.15031.

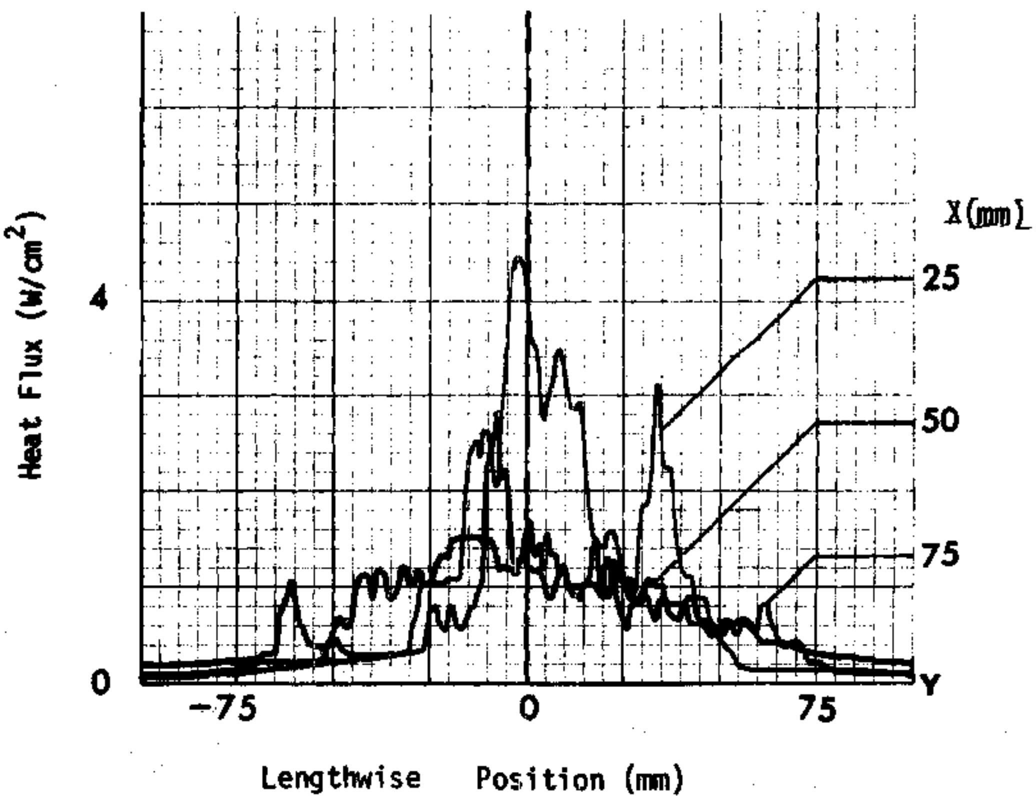

Figure 23. Height Effects on Heat Flux Distribution. In the Vertical Plane, at Z = 75 mm, in front of the Vertical Center Plane. Kenmore Gas Hot Plate Model No. 119.15031.

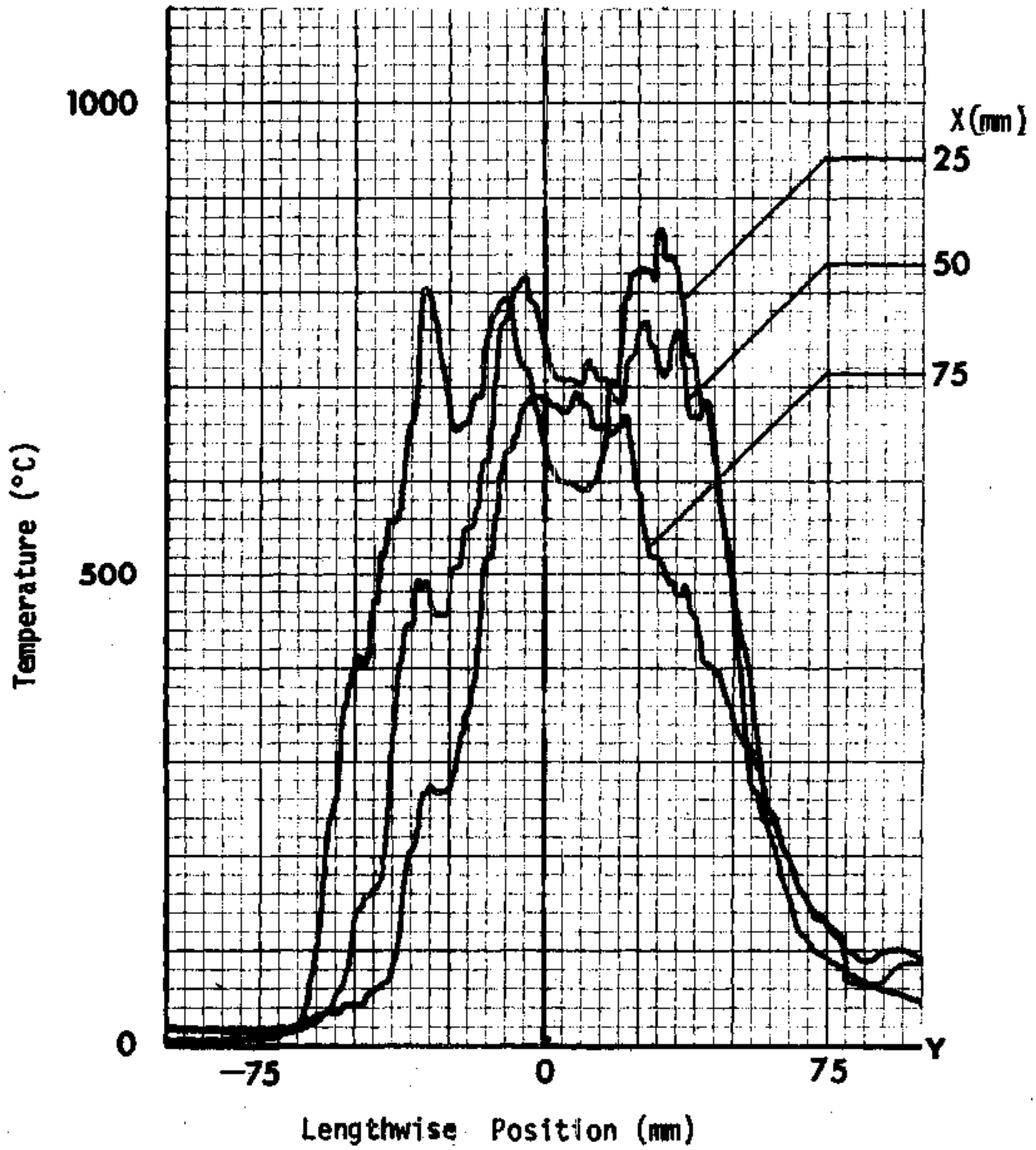

Figure 24. Height Effects on Temperature Distributions. In the Vertical Plane, at Z = 25 mm, in front of the Vertical Center Plane. Kenmore Gas Hot Plate, Model No. 119.15031.

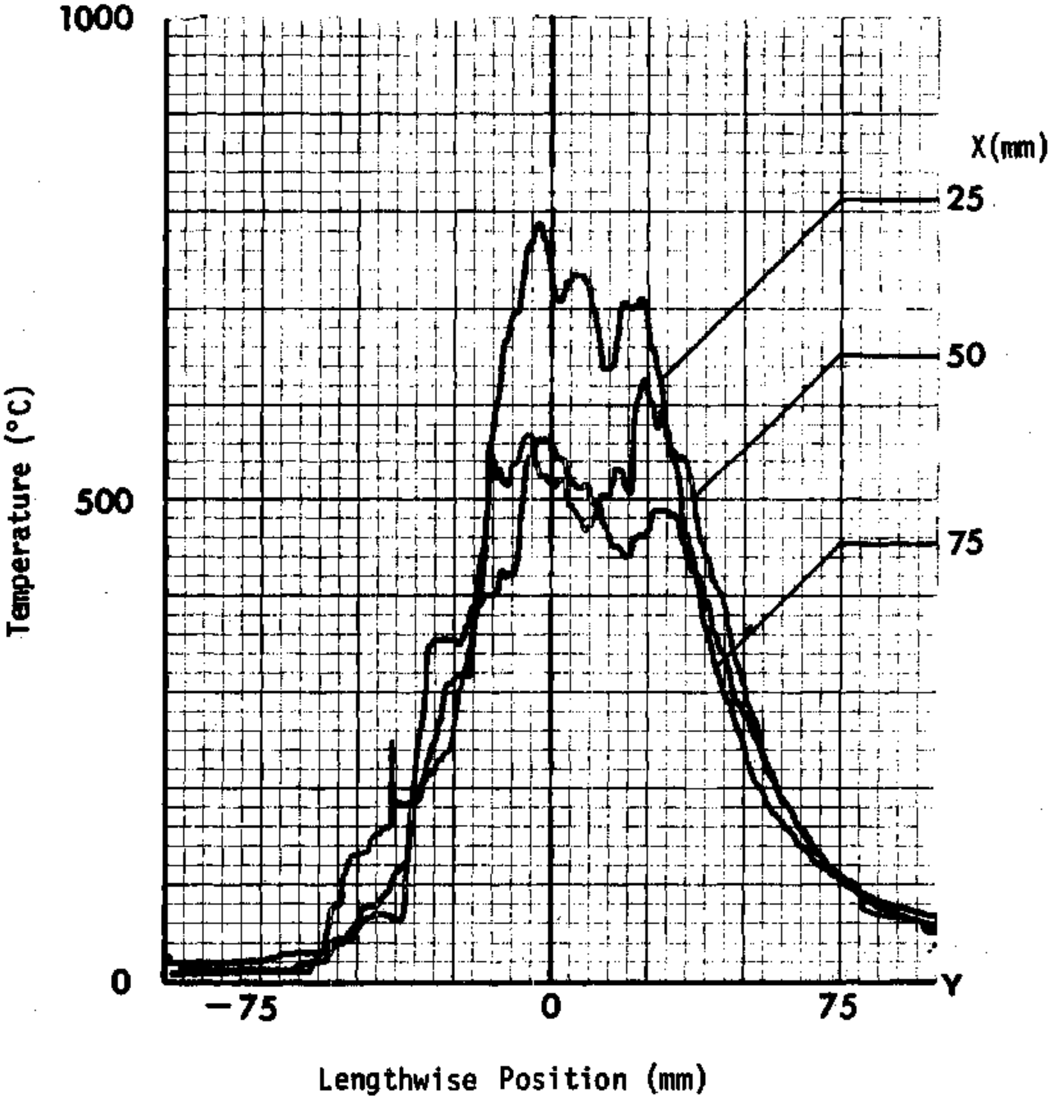

Figure 25. Height Effects on Temperature Distribution. In the Vertical Plane, at Z = 50 mm, in front of the Vertical Center Plane. Kenmore Gas Hot Plate, Model No. 119.15031.

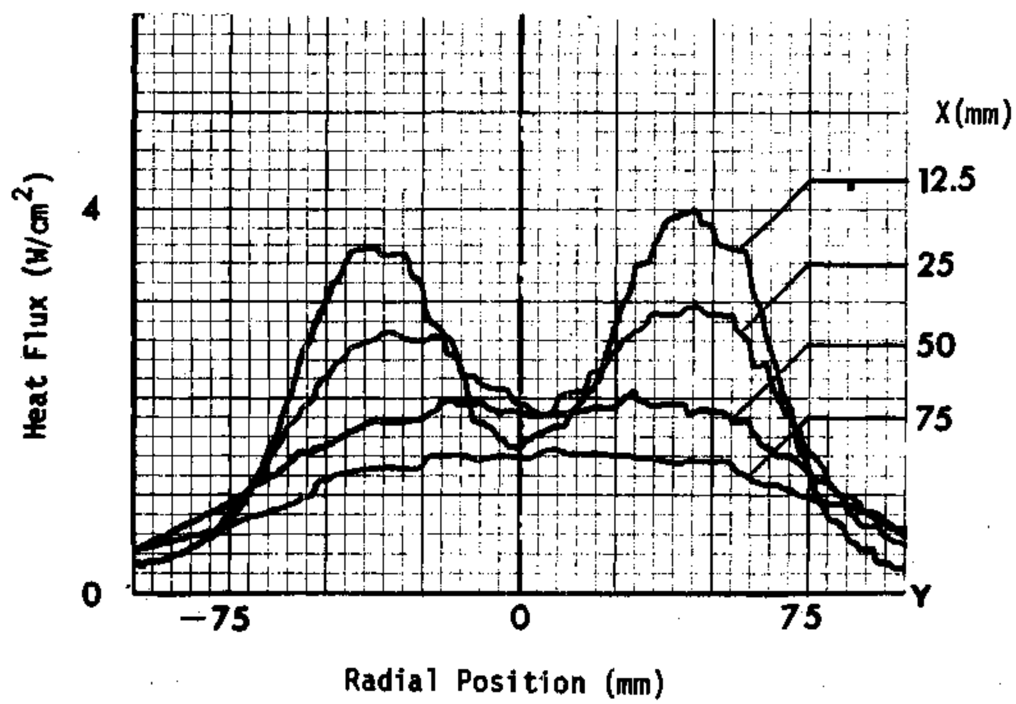

Figure 26. Height Effects on Heat Flux Distribution In the Vertical Center Plane. Open-Coil Hot Plate, 800 Watts.

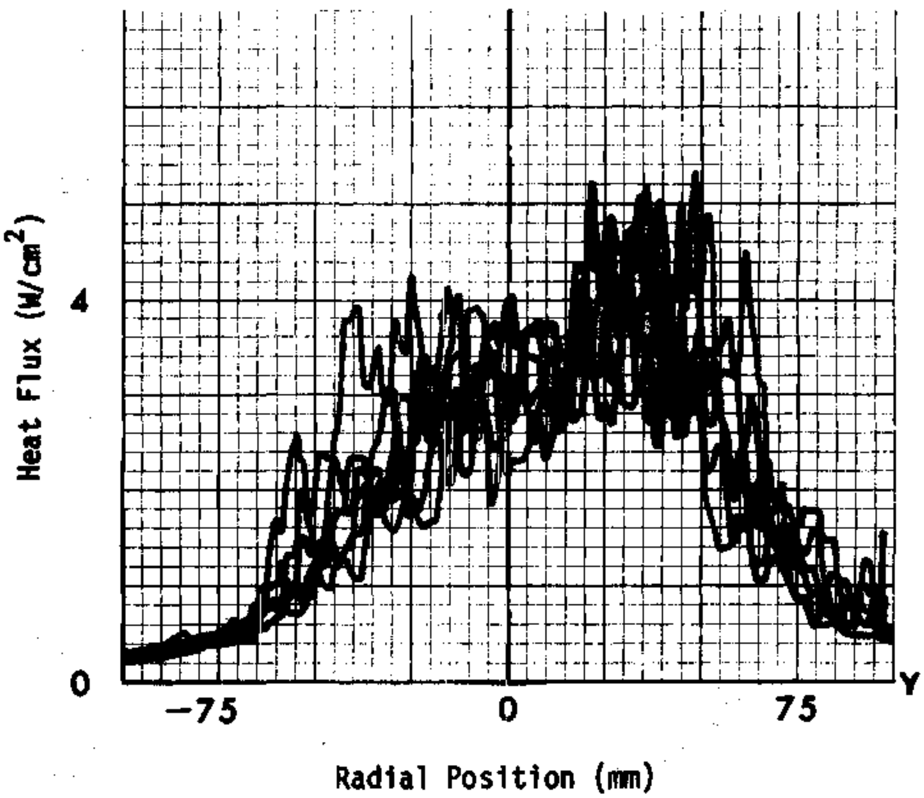

Figure 27. Influence on Heat Flux Distribution by Neighboring Burner at the Right-Hand Side. At X = 75 mm above Burner Top, in the Vertical Center Plane. Kenmore Gas Hot Plate, Model No. 119.15031.

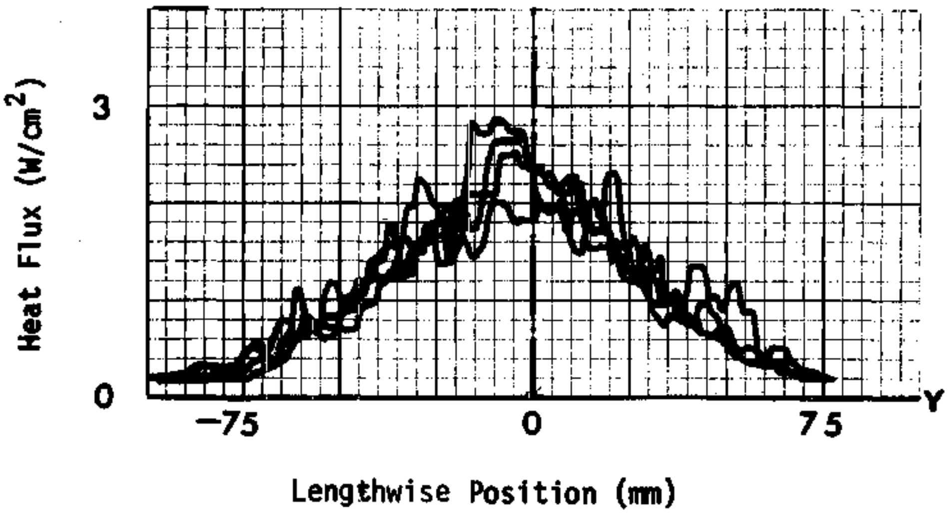

Figure 28. Peripheral Heat Flux Distribution of Covered Gas Flame.
Sauce Pan Diameter 150 mm. Measured in Vertical Plane, at Z = 100 mm, in Front of Center Plane. Kenmore Gas Hot Plate, Model No. 119.15031.

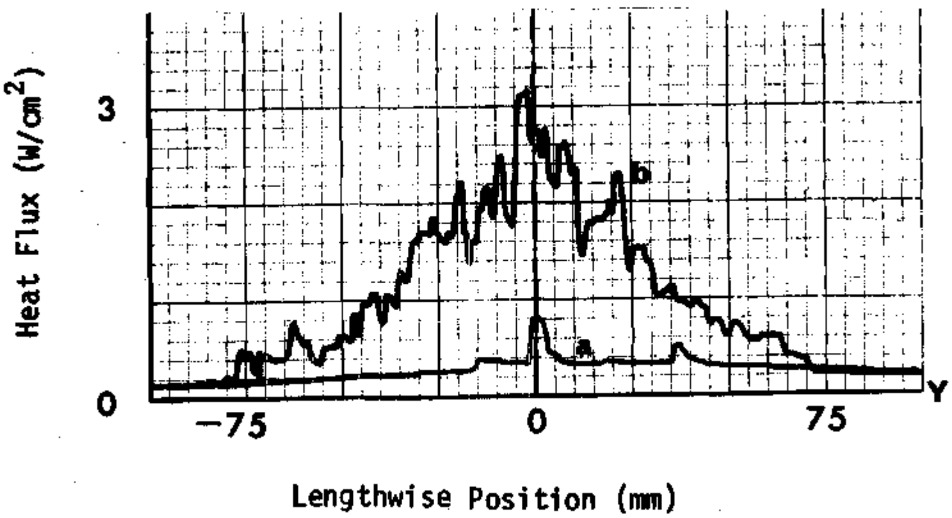

Figure 29. Deflection of Heat Flux by Cooking Ware.
Curve a, without Utensil.
Curve b, with 150 mm dia. Sauce Pan.
Measured in Same Plane as for Figure 28.

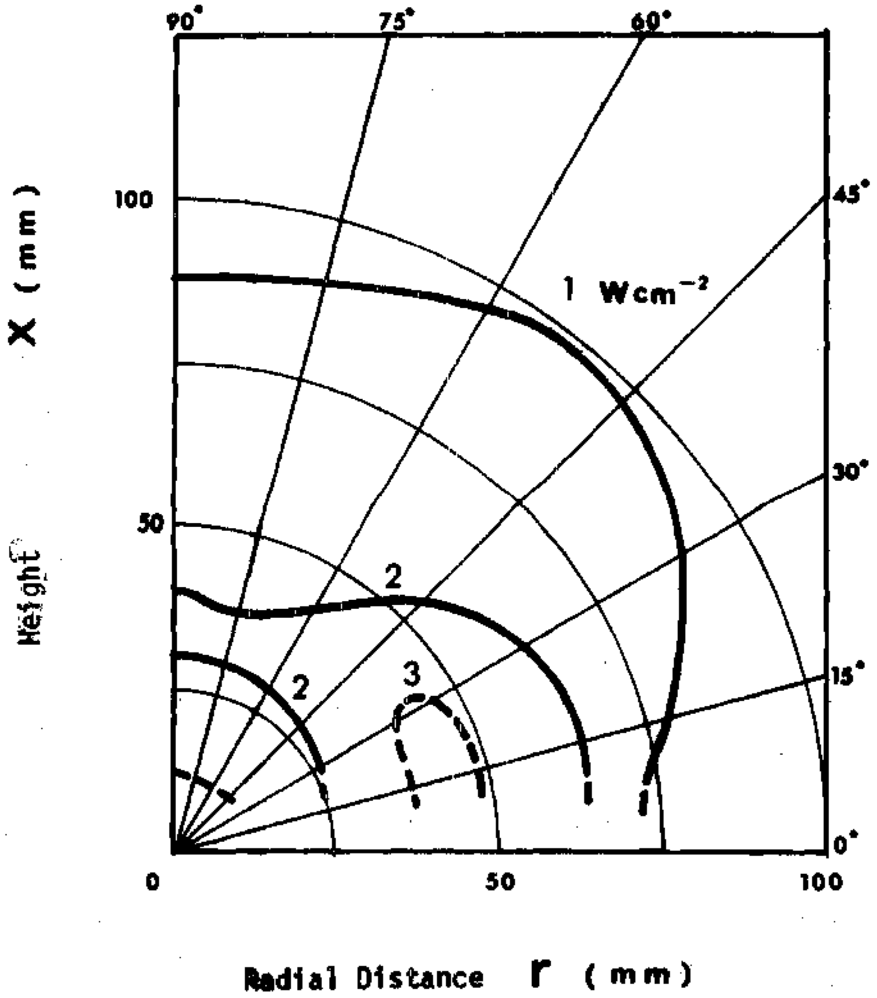

Figure 30. Total Vertical Heat Flux Distribution. Open-Coil Hot Plate 0.8 kW.

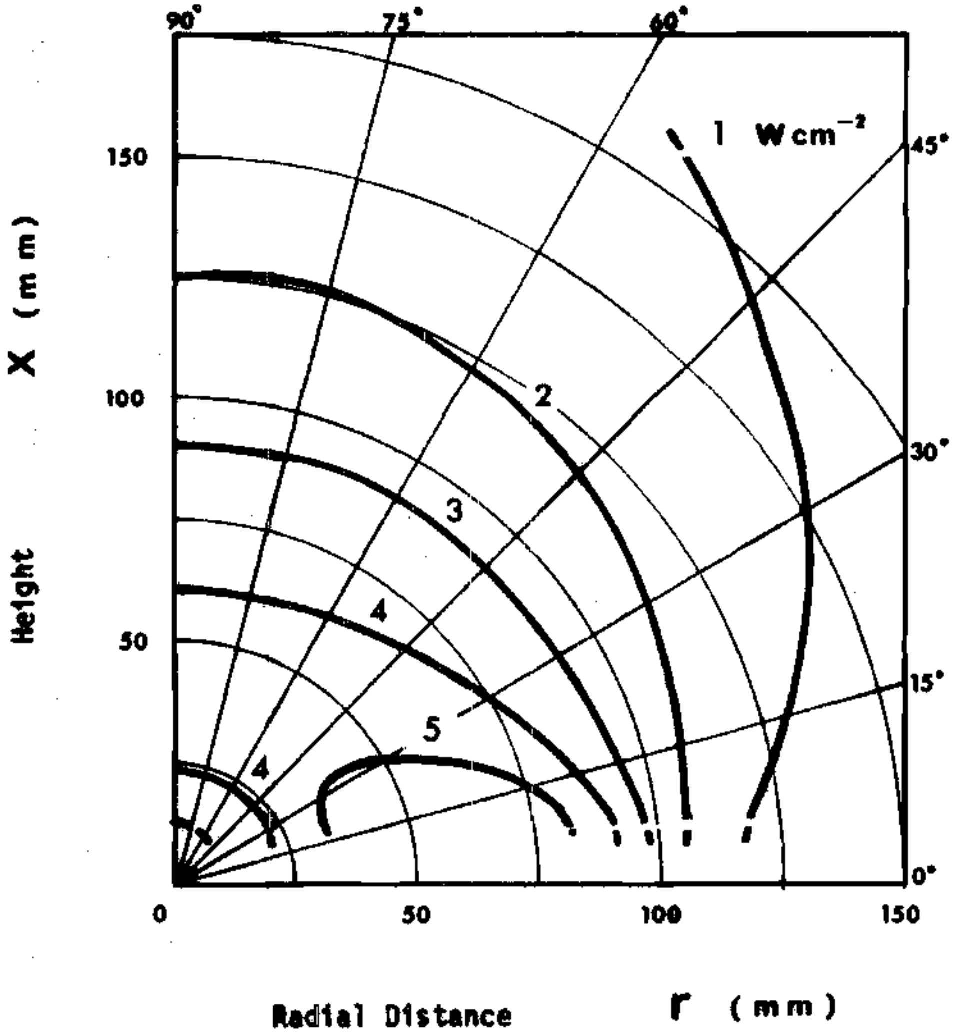

Figure 31. Total Vertical Heat Flux Distribution. Westinghouse Electrical Range 2.6 kW.

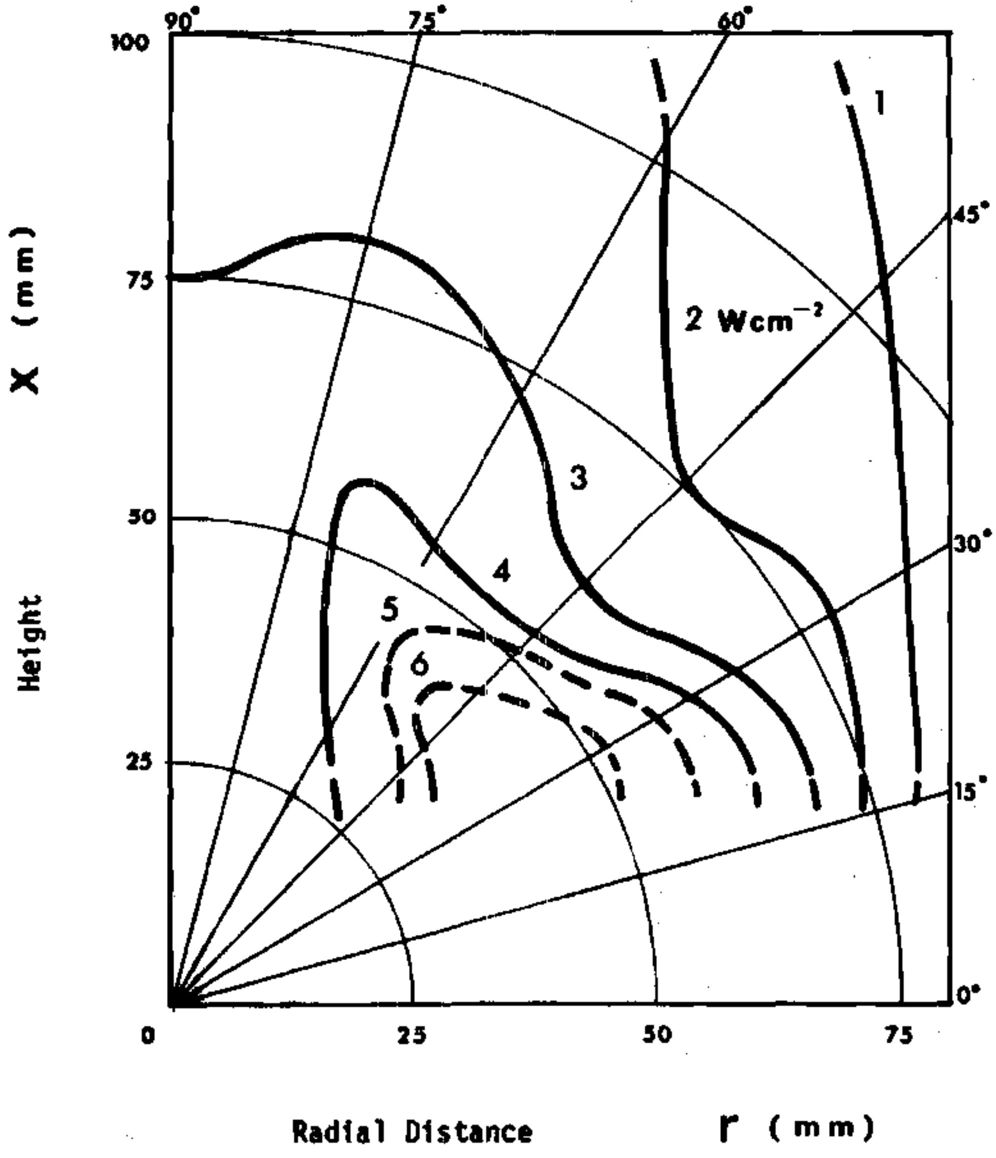

Figure 32. Total Vertical Heat Flux Distribution.
Kenmore Gas Range, Model No. 119.15031.

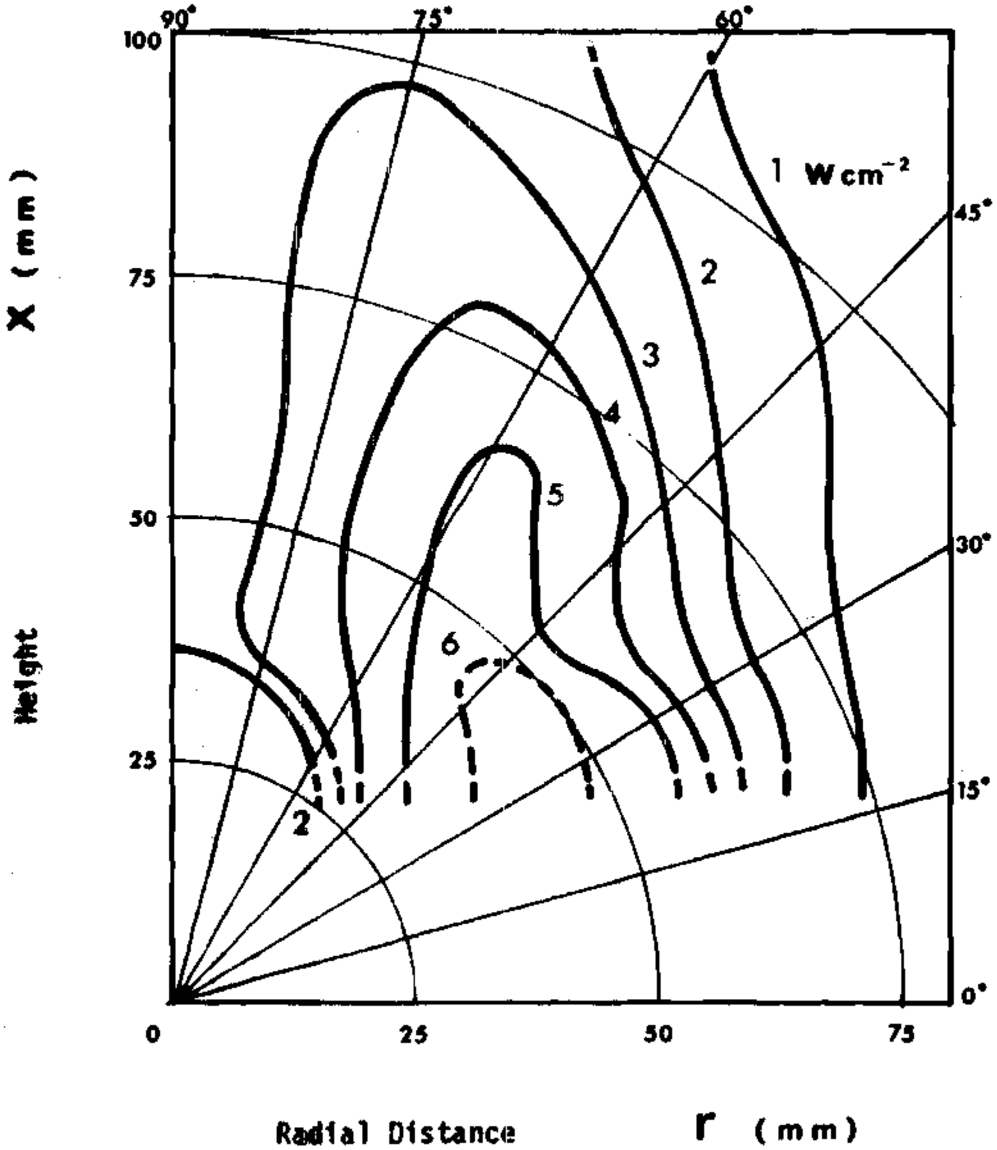

Figure 33. Total Vertical Heat Flux Distribution Sears Kenmore Series 71731.

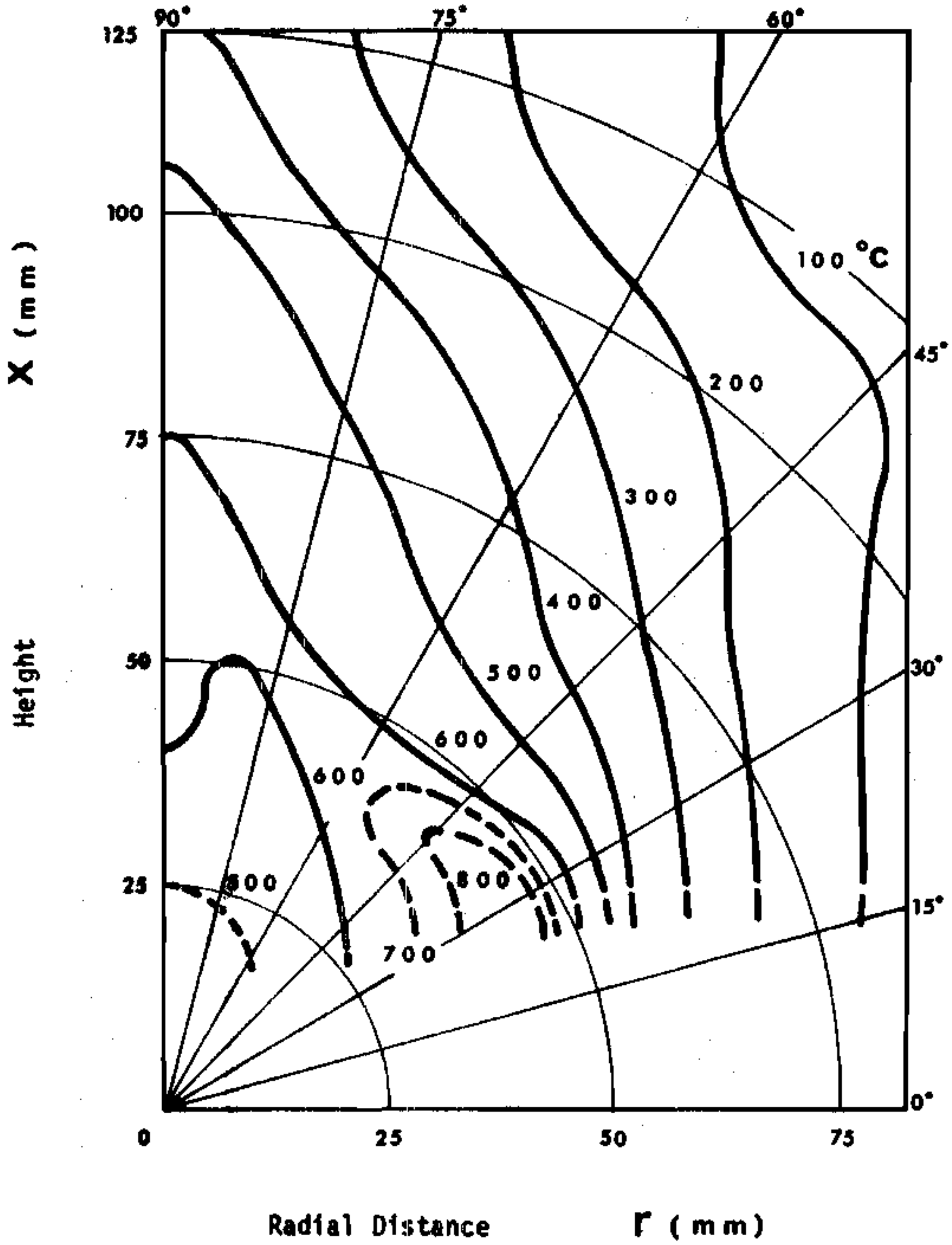

Figure 34. Vertical Temperature Distribution.
Kenmore Gas Range, Model No. 119.15031.

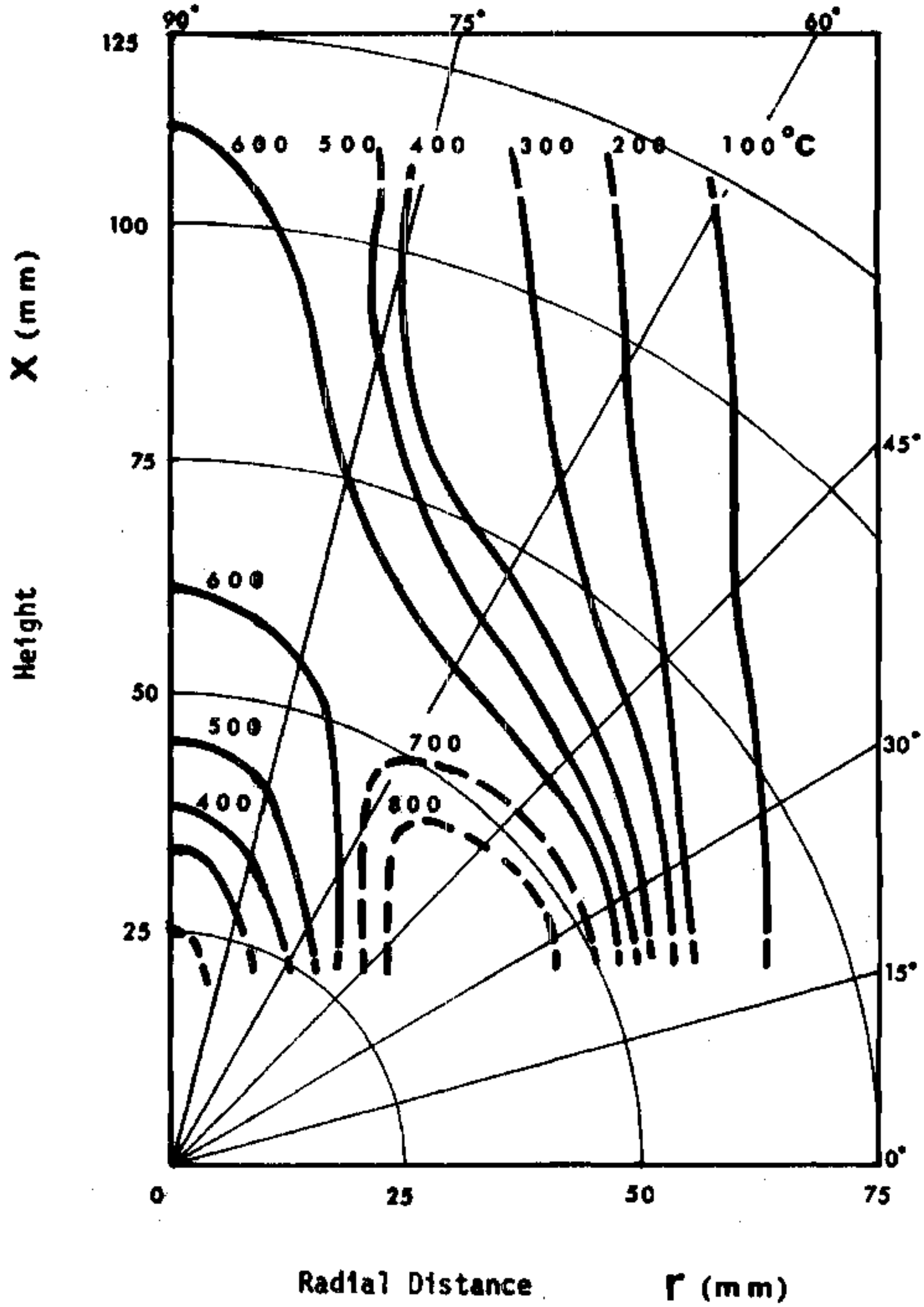

Figure 35. Vertical Temperature Distribution.
Sears Kenmore Series 71731.

(viii) The results from the measurements corresponding to 90° position between heat sensor and burner did not produce anything new in relation to the heat flux distribution with 0° position.

(ix) The averaged surface temperature for the radiative sources was 920°C for the open coil hot plate and 900°C for sheathed coil.

Cigarette lighters, matches, and candles were found to be too small for detailed heat flux and temperature measurements.

Table 7 summarizes the results obtained for the small sources based on two aspects, firstly, full burn studies [33] have revealed that ignition always occurred after the peak heat intensity has been reached, and secondly, studies carried out at FMRC [34] have shown that for methane diffusion flames the minimum ignition time for fabrics appears to result when the fabric is placed at the tip of the luminous flame and that the ignition time is quite insensitive to burner diameter, fabric orientation and flame height in the range of 0.5 to 1.0 inch.

Table 8 shows gas flow rates burned for the kitchen gas range in the laboratory and the supply pressure of the fuel.

Table 9 shows the heat sensor cooling water temperature. The high condensation on the heat sensor surface did not permit the use of cold water.

Table 7. Characterization of Small Ignition Sources

Ignition Source	Distance from Sensor	Averaged Height of the Flame	Expected Peak Heat Flux	Expected Peak Temperature	Expected Average Film Coefficient
	mm	mm	W/cm^2	°C	W/cm^2 °C
Matches	25	16	3.4	290	0.0136
		22	5.4	540	0.0108
		25	5.4	580	0.0100
Cigarette Lighter	25	50	5.8	--	--
	50	50	5.8	500	0.0126
Candle	25	25	7.8	650	0.0128
	50	25	4.6	300	0.0192

Table 8. Fuel Flow Rates and Supply Pressures for Kitchen Gas Range

No. of Burners Full Valve Opened	Supply Pressure mm H_2O	Fuel Flow Rates Lts/hrs
3	128.75	118.1
2	156.25	88.6
1	181.25	48.8
0	197.5	0.0

Table 9. Heat Flux Sensor Cooling Water Temperature Data

General Location	Source	Averaged Working Temperature °C	Temperature Variations °C
Laboratory	Gas Range, Matches, Cigarette Lighters, Candles.	40	± 2.0
	Electrical Range	13	± 0.5
Off-Campus	Gas Range	55	± 2.0
	Electrical Range	15	± 0.5

Conclusions

The heating intensity measurements produced the following conclusions.

(i) The larger the power of the kitchen electrical range's coil, the bigger the hazard it represents.

(ii) Sheathed coils have lower maximum heating intensity levels than open coils at maximum power, but they represent a larger surface to contact and better heat conduction to a fabric. The surface temperature of the open coil, with 800 watts, was found to be higher than that of the solid coil, with 2600 watts.

(iii) Heat flux and temperature distribution for the kitchen gas range are nearly independent of burner size.

(iv) The group of small sources showed to have relatively high heat fluxes. The closer one gets to the flame's tip, the larger is the heat flux and hence, the smaller is the ignition time.

CHAPTER VII

PROBABILITY OF IGNITION UNDER ACTUAL CONDITIONS

Previous Findings

The ultimate goal of fabric flammability studies is the assessment of the burn injury probability, a quantitative measure of burn injury hazard. A first and necessary step is, however, the prediction of the fabric ignition probability as discussed in Chapter IV.

The fabric ignition probability was determined for several fabrics under well-defined laboratory conditions, namely, exposure time and exposure conditions. Results are discussed in Chapter V.

Actual exposure conditions were evaluated for various common ignition sources, as shown in Chapter VI. However, statistics measurements on the behavior of people in the presence of ignition sources have not been carried out yet.

This chapter is concerned with the conceptual framework for exposure time studies, with the conceptual evaluation of the actual fabric ignition probability, and finally with a short discussion about the correlation of actual and laboratory fabric ignition probability.

Exposure Time Studies

A study of the actual behavior of the people in the proximity of an ignition source is still missing. Here is discussed a procedure to find the exposure probability to an ignition source.

The exposure time studies are confined to the vicinity of sources because the heating intensity falls off rapidly with the distance from the source, and therefore the ignition probability diminishes at short distances from source. The measurements must involve all the relevant factors associated with an exposure condition.

A decision tree for exposure studies of clothing fabrics is shown below in Figure 36. It presents some of the aspects which must be considered when exposure time studies are planned. They are age groups, activities and potential ignition sources. Once a fabric F_h has been tailored into a specific garment it is assumed to be worn by a member of a particular age group G_i. This individual can be engaged in several activities A_j, in each of which exposure to any one of several ignition sources may happen, determining thereby several types of exposure conditions E_k. Additional aspects can readily be accommodated.

The total probability of exposure type E_k for a given fabric F_h is the sum of the probabilities associated with all paths which, starting at F_h, lead to E_k, thus,

$$P(E_k/F_h) = \sum_{i=1}^{i=n} \sum_{j=1}^{j=m} P(G_i A_j E_k/F_h) \qquad (7.1)$$

Key : **F = Fabric** **A = Activity**

G = Age Group **E = Exposure**

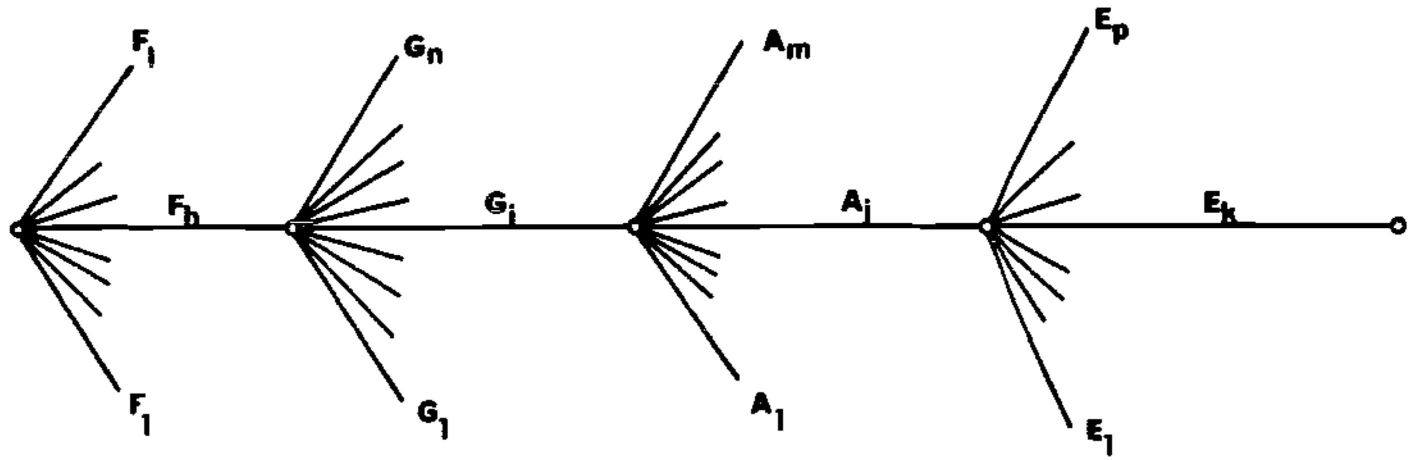

Figure 36. Decision Tree for Exposure Time Studies

where n are the total number of age groups considered and m the total group of activities associated with every age group.

Time of exposure and distance from ignition source are the key parameters of exposure description. Times can be measured by means of stopwatches and distances can be measured by visual observations. Distance may be defined as the closest distance from fabric to heat-producing element of ignition source regardless of its orientation. Distance from source may be considered in cumulative intervals.

Some results to be obtained from the exposure time studies are: (i) times spent in a given interval for a given source, (ii) ignition source use frequency on a daily basis, (iii) fabric use frequency.

Therefore, for a given age group, a given activity, ignition source and fabric, one will have a series of times spent in a given interval of distance from the source. These times must be normalized by the observation period and converted to daily basis, using the ignition source use frequency. The normalized exposure times, τ_e^*, can be plotted against midpoint class intervals, r_w. One might expect that the observed and normalized exposure time at a given distance from the source follows a normal probability distribution, because of its dependence on a large number of independent causes, or in other words, because of the Central Limit Theorem. Figures 37 and 38 depict the above idea.

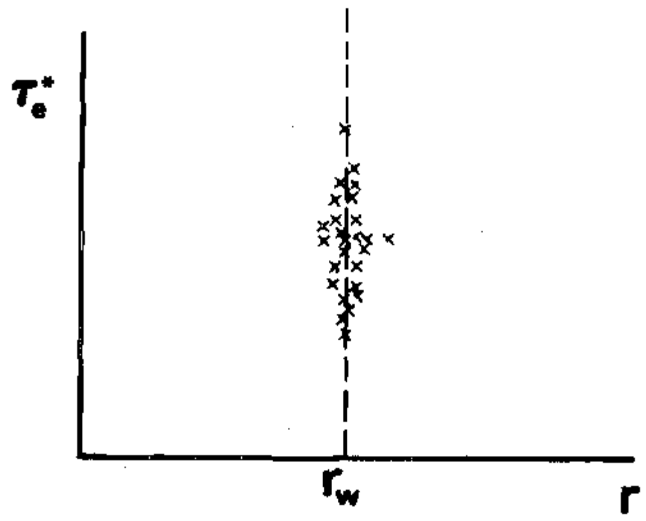

Figure 37. Observed Normalized Exposure Time as Function of the Distance from the Ignition Source

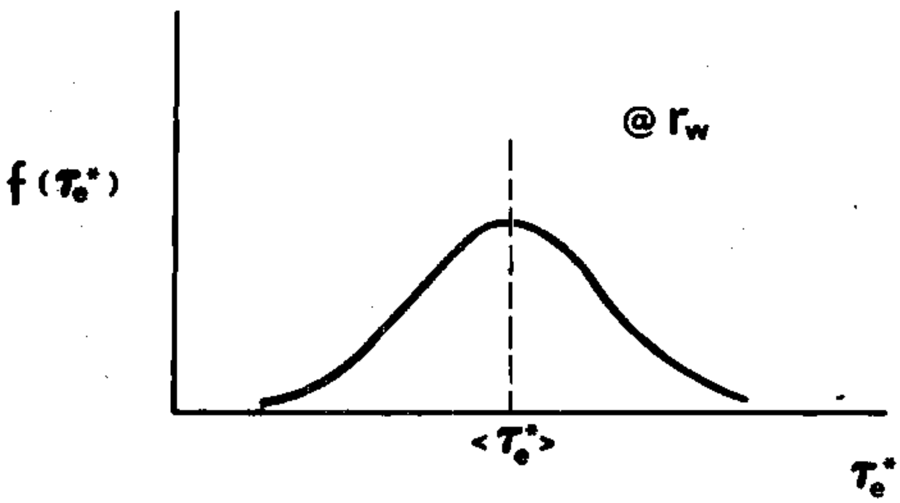

Figure 38. Expected Probability Distribution Density for Observed Normalized Exposure Time

Cumulative relative frequency of normalized exposure time can tentatively be formed and approximated to the exposure probability $P(E_kA_jG_i/F_h)$ at r_w, thus,

$$P(E_kA_jG_i/F_h)_{r_w} = \frac{\text{number of observations where } \tau_e^* \leq \tau_{ei}^*}{\text{total number of observations}} \quad (7.2)$$

where τ_{ei}^* is a given value of τ_e^*.

Figure 39 depicts an expected cumulative distribution curve.

Even if $P(E_kA_jG_i/F_h)$, at a distance r_w from the source, were not normally distributed, once one sums over a very large number of age groups and activities, one obtains the resulting probability $P(E_k/F_h)$ which can be assumed to be approximately normal because of the Central Limit Theorem. If the individual probabilities $P(E_kA_jG_i/F_h)$ have a mean value μ_i and a finite variance $\sigma_i{}^2$, then $P(E_k/F_h)$ is said to be normally distributed with mean value,

$$\mu = \sum_{i=1}^{i=nxm} \mu_i \quad (7.3)$$

and variance,

$$\sigma^2 = \sum_{i=1}^{i=nxm} \sigma_i{}^2 \quad (7.4)$$

It is expected that the S-shape curve shifts to the right as the range distance interval grows, that is, r_w

increases, because of the natural tendency of people to remain as far as possible from heat sources. Figure 40 illustrates this idea.

Lines of constant probability can be obtained by replotting the previous figure as shown in Figure 41. Any intermediate value can be readily found by linear interpolation.

The Actual Fabric Ignition Probability

The actual conditions have been analyzed in Chapter VI for several ignition sources. The exposure conditions, namely, the heating intensity and temperature levels, are presented in polar coordinates. It was demonstrated in principle how the probability with which a given exposure duration is encountered on a daily basis.

The probability with which a certain exposure condition is actually found, that is, the fraction of time during which the given fabric is exposed to a given heating intensity and environmental relative humidity and initial temperature is expected to follow a normal probability distribution because of the Central Limit Theorem, and the previous results obtained in the laboratory. Therefore,

$$P_{r\ell}\ (I/E_k F_h X) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\lambda^*} \exp(-z^2/2)dz \qquad (7.5)$$

the subscript $r\ell$ means real life conditions, X means environmental conditions. The upper integration limit is

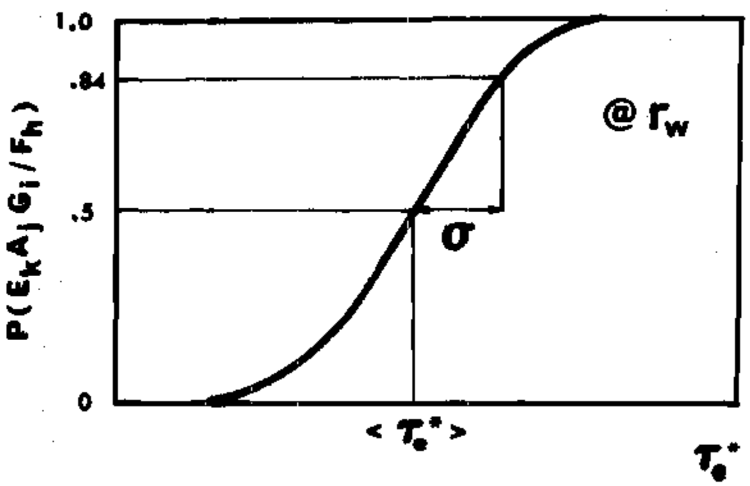

Figure 39. Expected Distribution Function for Observed Normalized Exposure Time

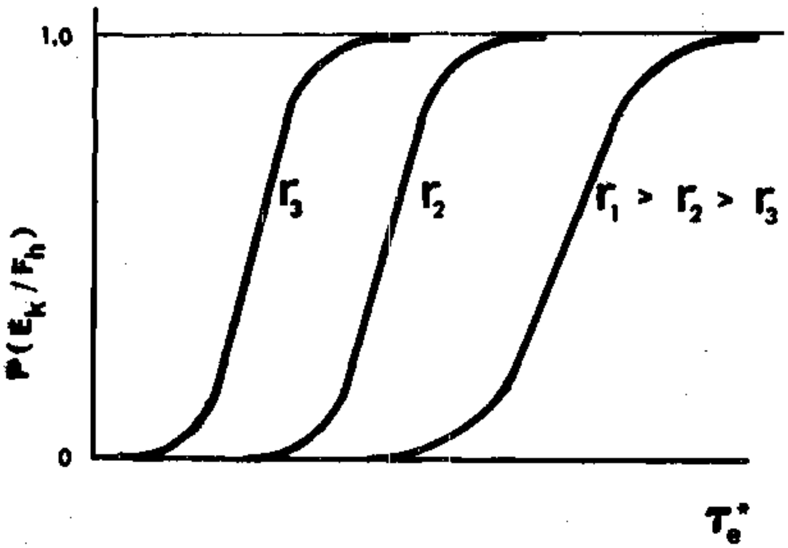

Figure 40. The Exposure Probability as a Function of the Distance from Source Center

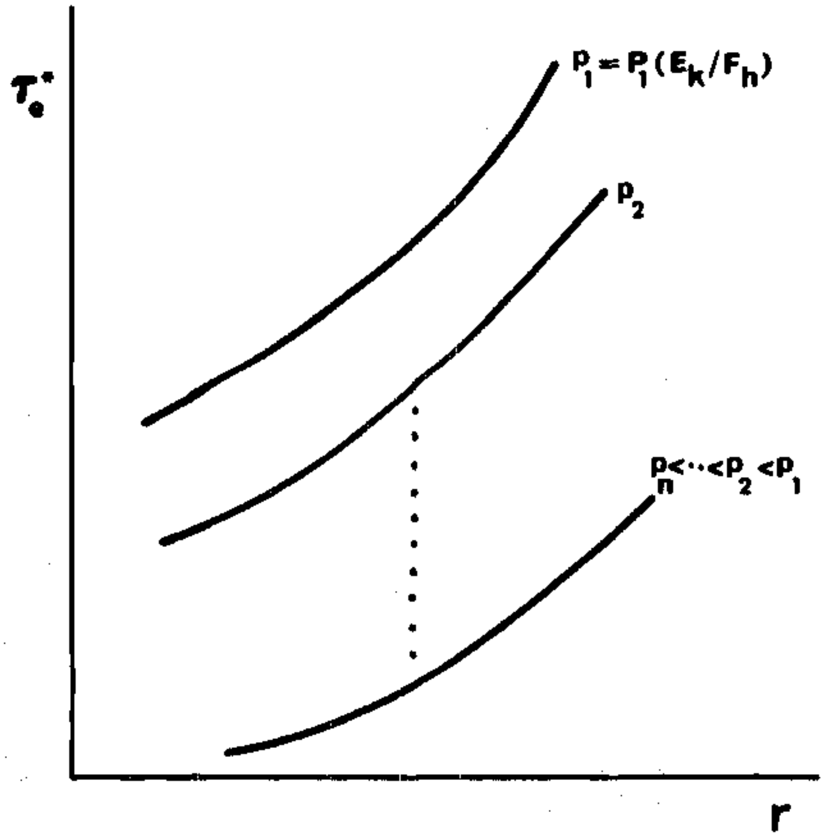

Figure 41. Lines of Constant Exposure Probability

given by

$$\lambda^* = \frac{\tau_e^*/\langle\tau_i\rangle - 1}{\sigma} \tag{7.6}$$

where

$$\langle\tau_i\rangle = \tau_i[w_o(r,\phi),X] \tag{7.7}$$

and

$$\sigma = \sigma[w_o(r,\phi),X] \tag{7.8}$$

The probability with which a certain τ_e^* at r_w from a source is found in real life can be drawn from exposure time study results.

The relative frequency with which environmental conditions occur are obtained from climatological and space conditioning data, and it is defined as P(X).

Finally, the fabric ignition probability is tentatively given by

$$P(IE_kX/F_h) = P(\tau_e^*).P(X).P_{r\ell}(I/E_kF_hX) \tag{7.9}$$

for every possible type of exposure E_k associated with a given ignition source.

Here $P(\tau_e^*)$ is the probability to expose a fabric for the period τ_e^* to the conditions {X}. It is obtained as the ratio of the product $q.\tau_e$ divided by the time of observation; q represents the number of entries into the domain {X} and τ_e the duration of continuous residence in that domain. $P_{r\ell}$ has been defined before.

Given the position (r,ϕ) with respect to an ignition source, one can obtain the value of the heating intensity from the polar diagrams. Variance of the distribution and mean ignition time are functions of the heating intensity and humidity as shown in Chapter V. Hence, these variables are readily evaluated. Besides, if a residence time at the given position is known, the actual fabric ignition probability can be evaluated for the above conditions by substituting the given values in equation 7.9.

To repeat that calculation for every set of values is rather cumbersome, but it can be simplified by graphical representations for the equations. Figure 42 below shows lines of constant fabric ignition probability for a given heating intensity as function of r and ϕ for various exposure times.

A further simplification can be achieved for some sources by approximating every line of constant heat flux by a circular arc, see Figure 43. This eliminates the angular position of the calculations, leaving the heat flux as a function of the radius vector r only. This representation is shown in Figure 44 below. Figure 42 is then simplified

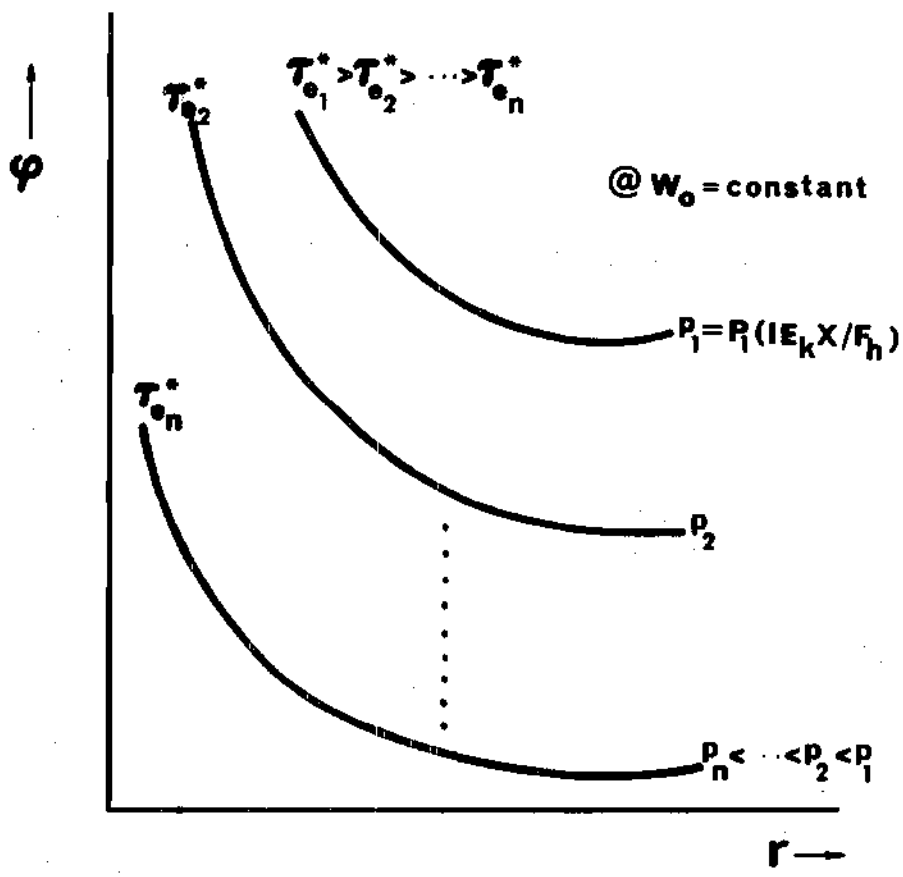

Figure 42. Lines of Constant Fabric Ignition Probability

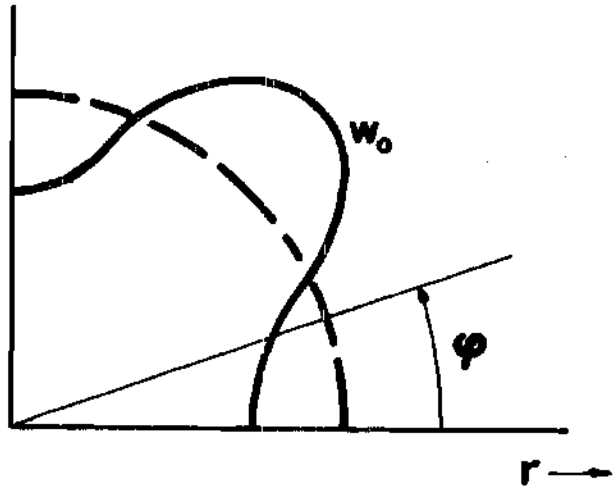

Figure 43. One-Dimensional Equivalent Heat Flux Distribution

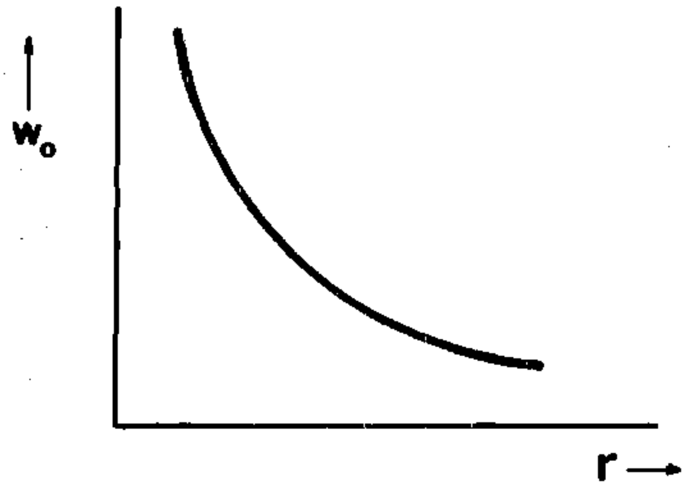

Figure 44. Simplified Heat Flux Distribution for an Ignition Source

as illustrated in Figure 45 where the probability $P(IE_kX/F_h)$ is shown in terms of distance or heating intensity.

Correlation of Laboratory and Field Test Results

The actual use fabric ignition probability can be computed from the probability of encountering in real life simultaneously a given heating intensity and a given time of exposure. This probability is multiplied with the laboratory ignition probability evaluated for the same heating intensity and exposure time. The relation is found in the Extension Rule.

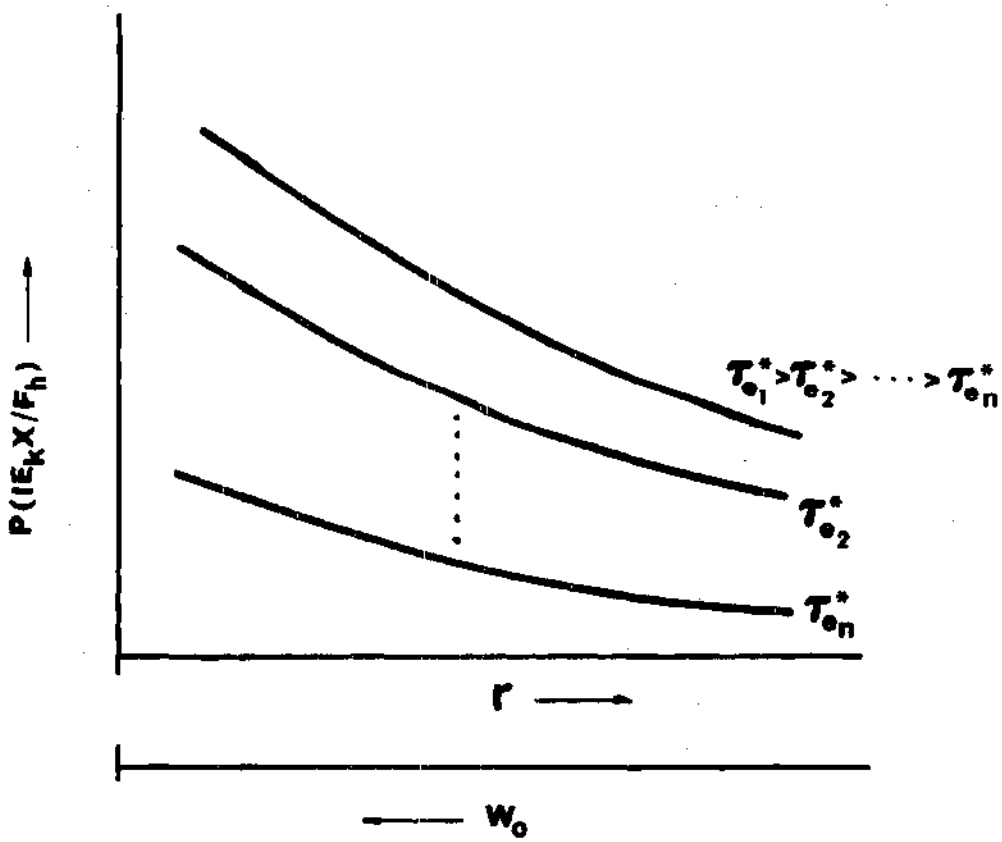

Figure 45. Simplified Presentation of Lines of Constant Fabric Ignition Probability

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

The desired goal to be obtained from the fabric flammability studies is the determination of the relationship between fabric behavior in a test method and the hazard it presents in actual use. This relationship is necessary in order to develop meaningful standards. The use of Decision Theory permits us to find that relationship in terms of probabilities.

The burn injury probability is a measure of the hazard represented by a fabric. Its direct evaluation is not possible. Associated events must be considered first in order to determine that probability. Two of these associated events are the exposure of a fabric to an ignition source and its eventual ignition.

This work has been concerned with the determination of the fabric ignition probability. It was intended to discuss the principles involved rather to complete a numerical evaluation of the burn injury probability.

Conclusions

The general conclusions from this research are summarized as follows:

(i) Garment fabrics are most commonly ignited, and the victim's residence is the most frequent location of fabric ignition accidents reported. Obviously, the most frequent heating sources of ignition are found in homes, namely, kitchen gas ranges, smoking materials and flammable cleaning liquids.

(ii) At 30% relative humidity with radiative heating, one can state that the greater the heat intensity the lower is the mean ignition time of the fabrics, the lower is the standard deviation of mean ignition time and of ignition time itself, and the narrower is the confidence interval of the ignition time. At 90% relative humidity there are some deviations from this tendency in all fabrics studied.

(iii) The actual ignition sources have a definite spatial heat flux and temperature distribution and the heat flux is low enough at a rather short distance from the source to require a very long exposure time to ignite most of the GIRCFF fabrics. The convective sources present higher fluctuations on their heat flux distributions and the variance of the ignition probability is expected to be greater than for radiative sources already studied.

(iv) The actual fabric ignition probability can be readily evaluated once the exposure time studies have been carried out.

Recommendations

Future research must be oriented toward the completion of the following objectives:

(i) The statistics data collection must be performed to include not only the serious accidents but also the small accidents seldomly reported. One must also gather all the information needed to obtain the relative frequencies characteristic of the selection processes.

(ii) Exposure time studies must be carried out in order to evaluate the actual probabilities involving exposure, in the decision tree of fabric flammability studies.

(iii) Ignition times in composite fabrics are to be determined because one must know about the influence of other fabrics on the behavior of a single layer fabric.

(iv) Laboratory studies oriented toward the determination of the fabric ignition probability under convective heating must be carried out.

(v) Characterization of actual ignition sources not considered in this study is to be done.

APPENDICES

APPENDIX A

FABRIC IDENTIFICATIONS

This appendix contains the identification of the three GIRCFF fabrics for which the probability of ignition was evaluated in the laboratory.

Table 10. Fabric Identification

GIRCFF No.	Classification	Fiber Composition	Color	Finish
5	T-Shirt, Jersey	100% Cotton	White	--
10	Batiste	100% Cotton	Purple	--
12	Tricot	100% Nylon	White	--

APPENDIX B

SUMMARY OF RESULTS FOR IGNITION SOURCE CHARACTERIZATIONS

This appendix contains the data needed for the evaluation of the total Vertical Heat Flux and Vertical Temperature Distributions.

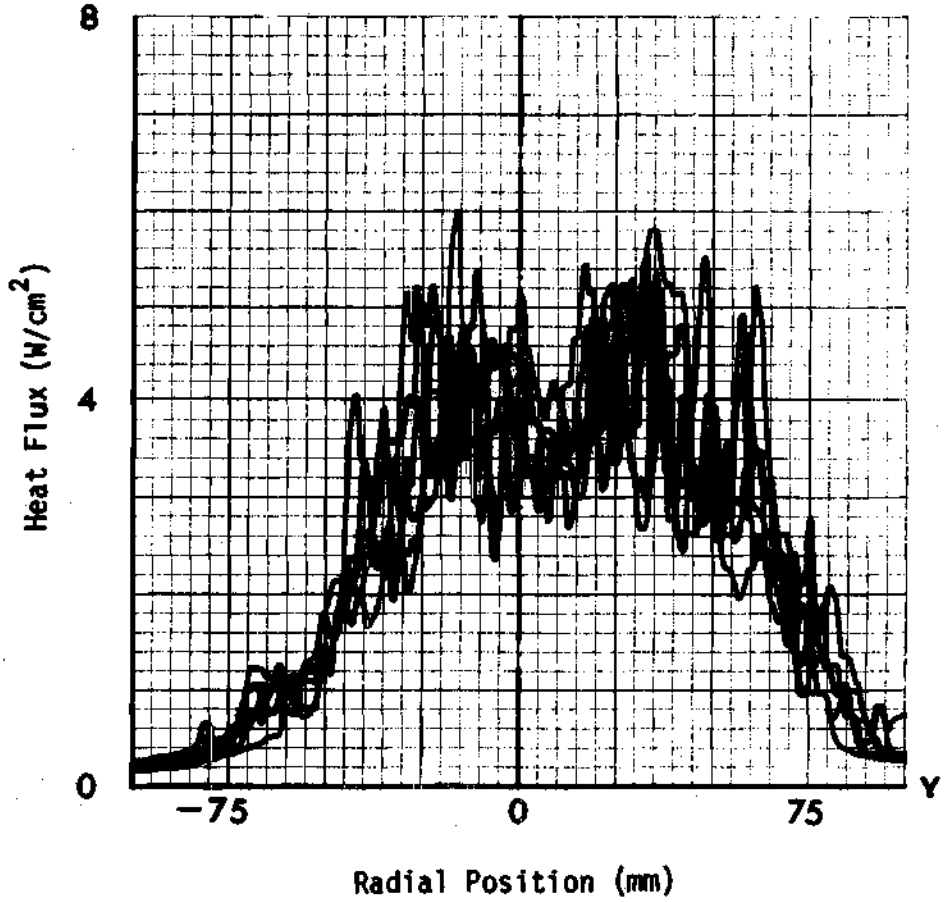

Figure 46. Heat Flux Distribution At X = 50 mm above Burner Top, in the Vertical Center Plane. Kenmore Gas Hot Plate, Model No. 119.15031.

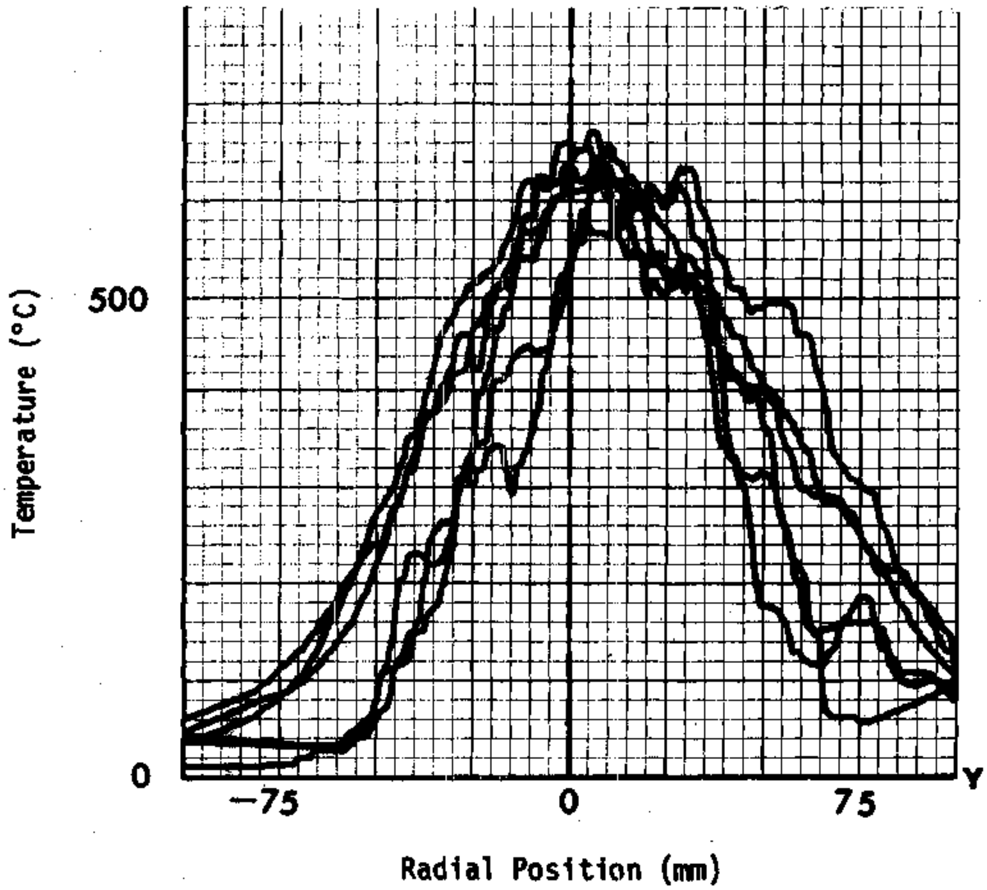

Figure 47. Temperature Distribution At X = 75 mm above Burner Top, in the Vertical Center Plane. Kenmore Gas Hot Plate, Model No. 119.15031.

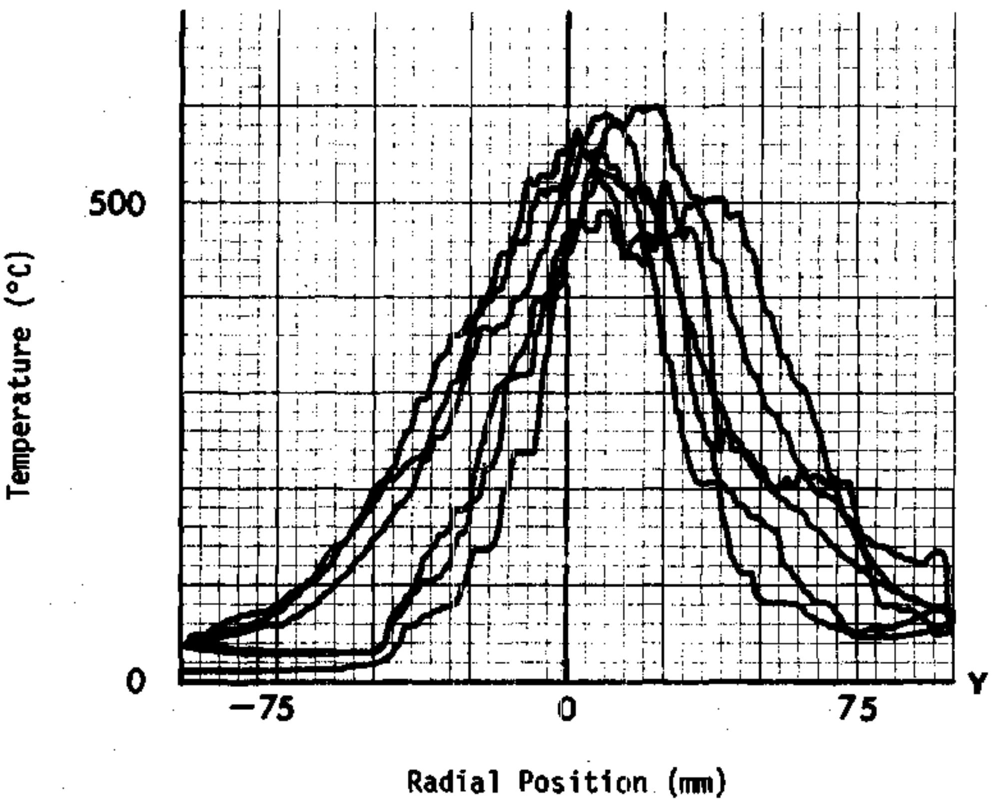

Figure 48. Temperature Distribution
At X = 100 mm above Burner Top,
in the Vertical Center Plane.
Kenmore Gas Hot Plate, Model No.
119.15031.

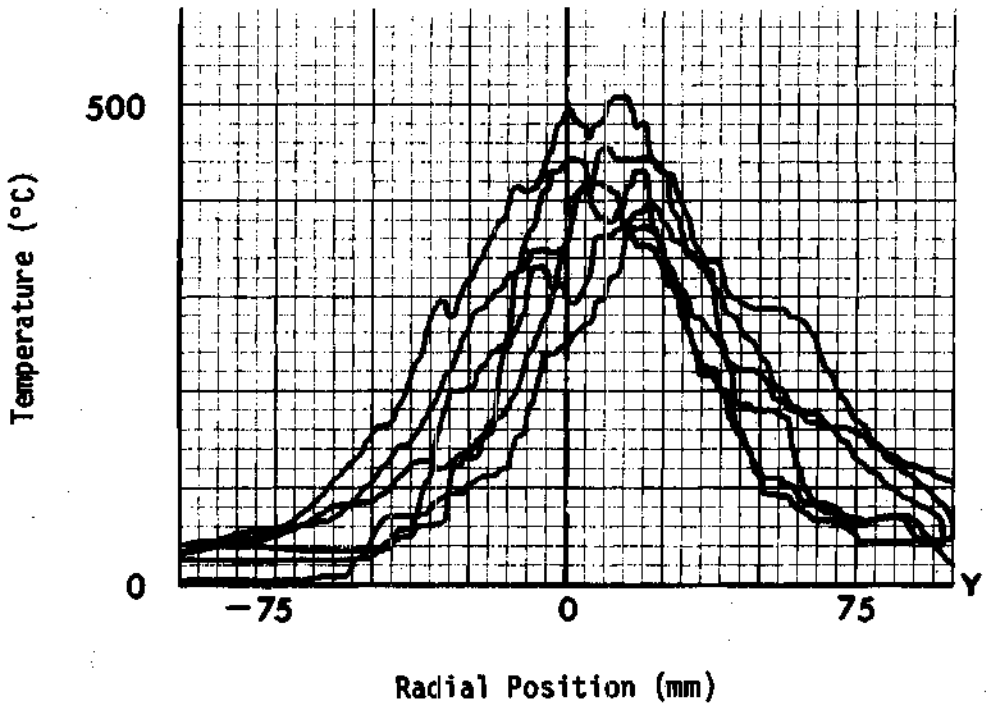

Figure 49. Temperature Distribution At X = 125 mm above Burner Top, in the Vertical Center Plane. Kenmore Gas Hot Plate, Model No. 119.15031.

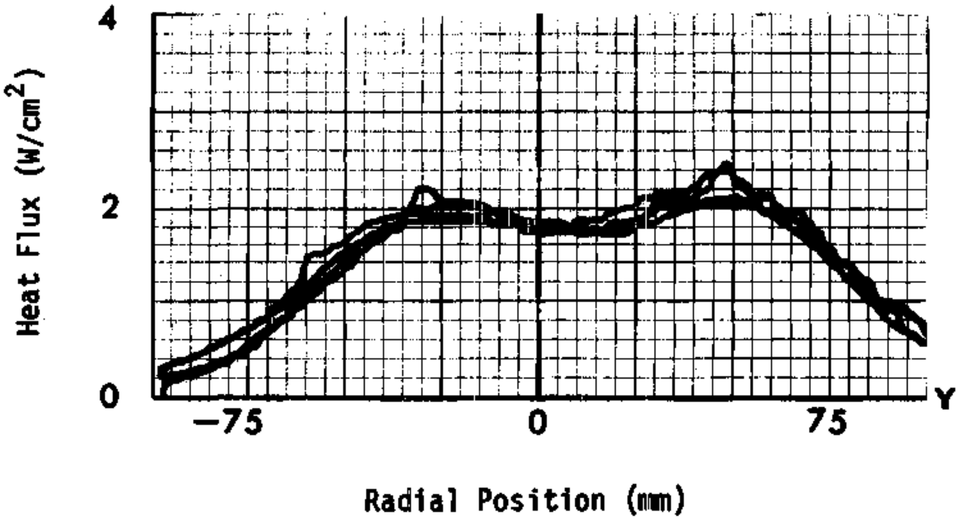

Figure 50. Heat Flux Distribution At X = 37.5 mm above Ceramic Base Top, in the Vertical Center Plane. Open-Coil Hot Plate, 800 Watts.

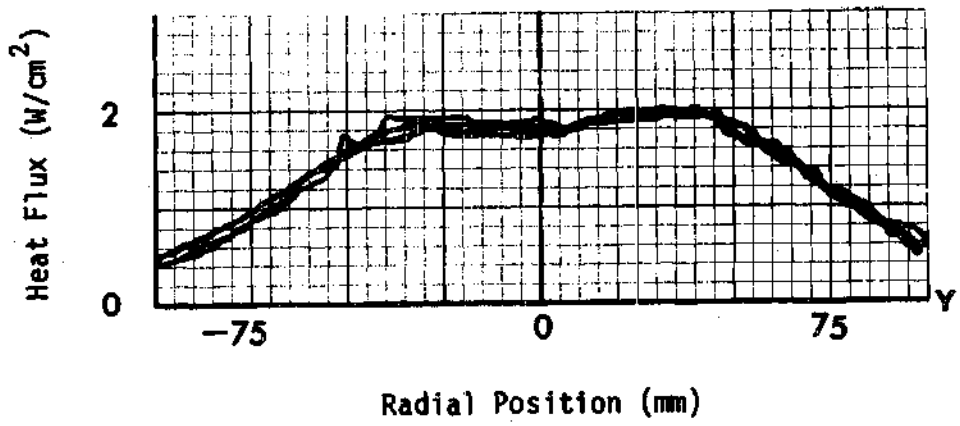

Figure 51. Heat Flux Distribution
At X = 50 mm above Ceramic Base Top, in the Vertical Center Plane. Open-Coil Hot Plate, 800 Watts

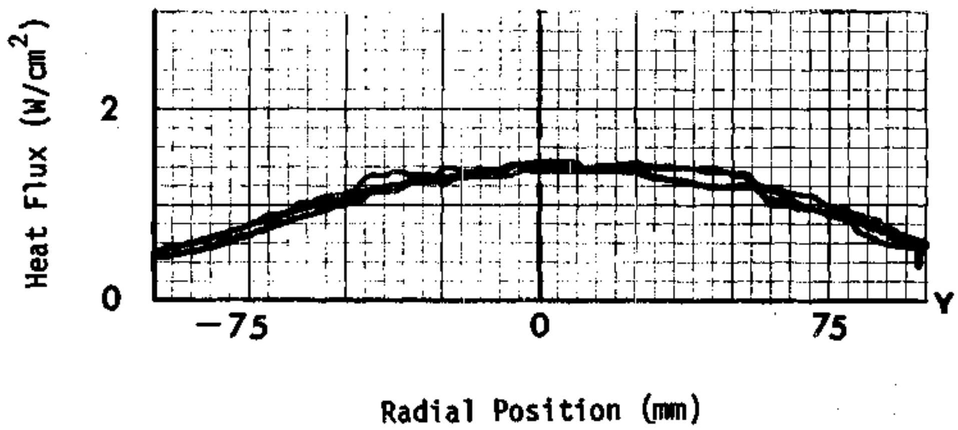

Figure 52. Heat Flux Distribution
At X = 75 mm above Ceramic Base Top, in the Vertical Center Plane. Open-Coil Hot Plate, 800 Watts.

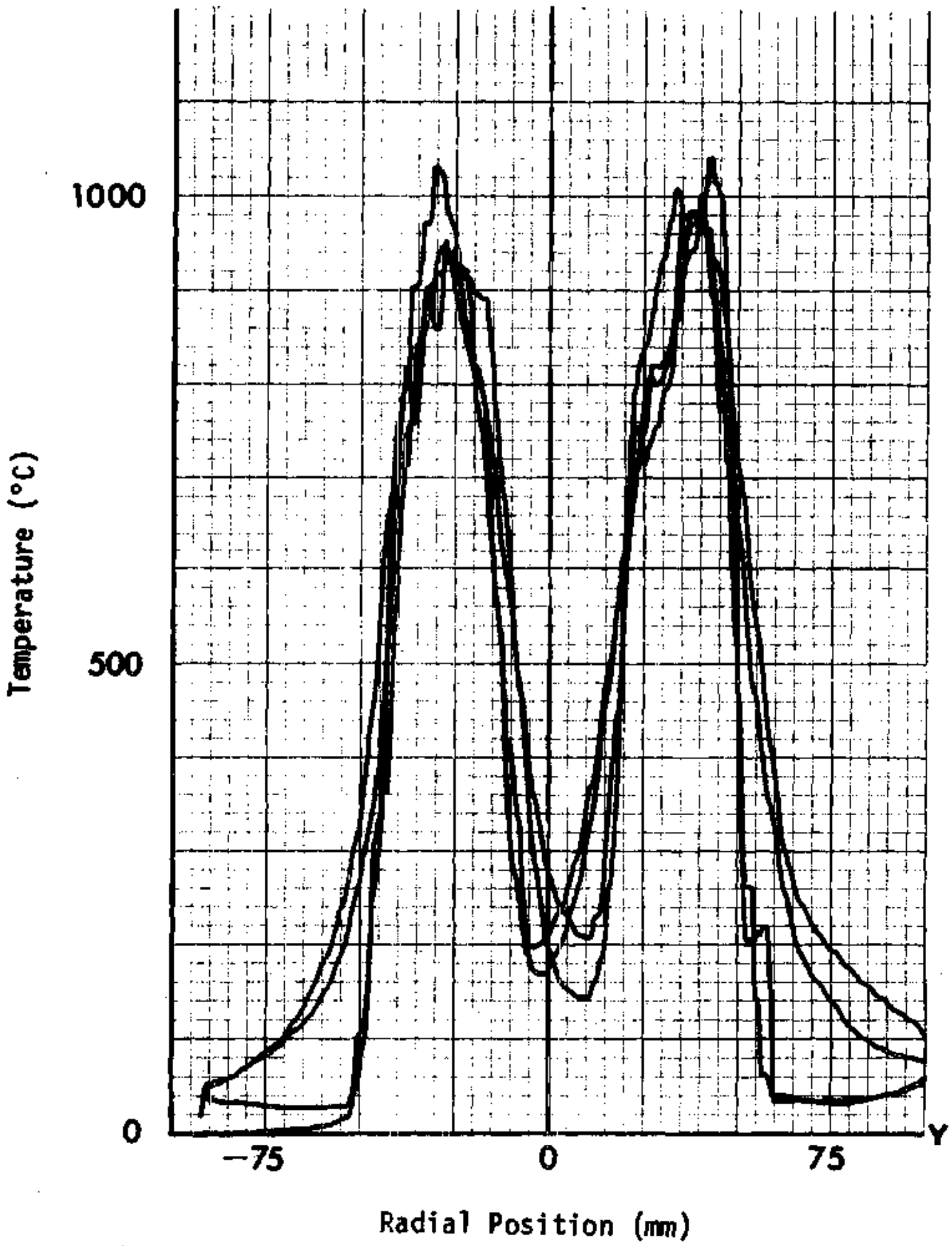

Figure 53. Temperature Distribution
At X = 25 mm above Larger Burner Top, in the Vertical Center Plane. Sears Kenmore Series 71731.

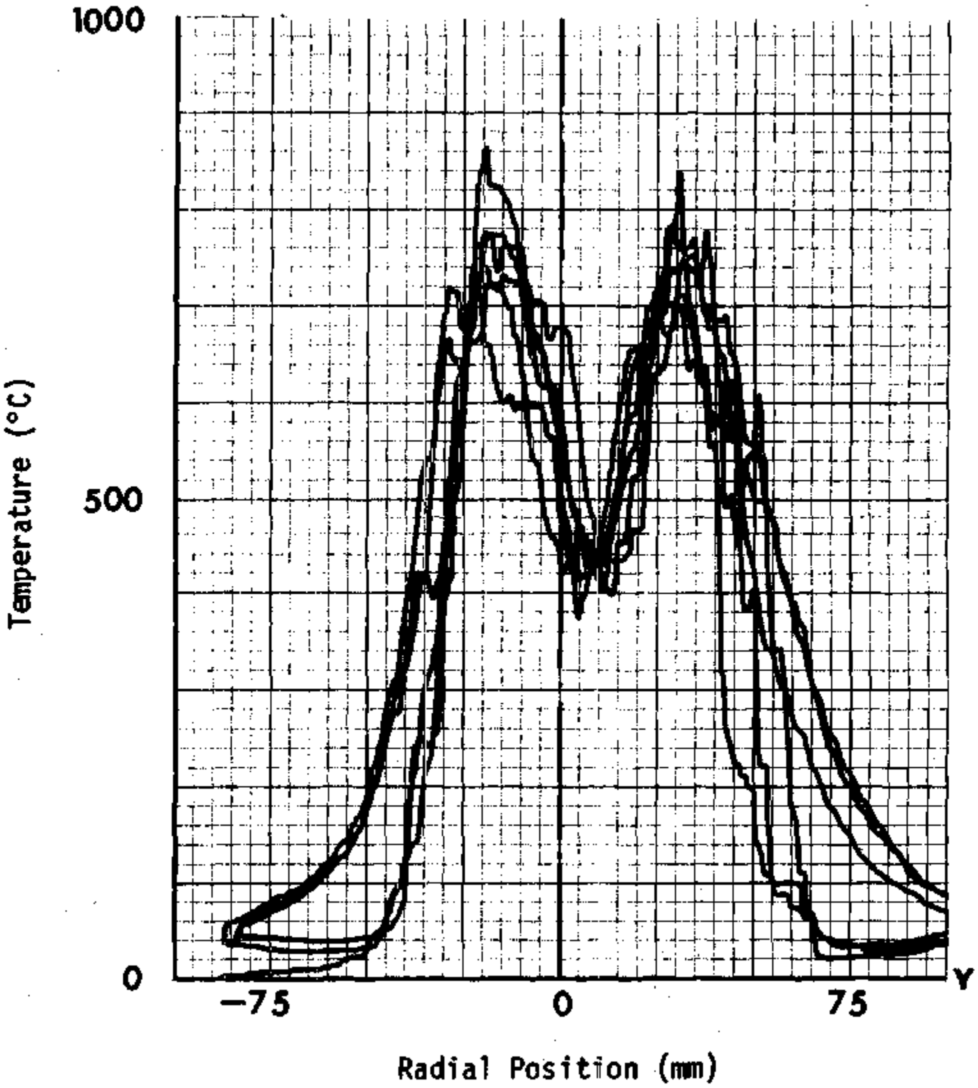

Figure 54. Temperature Distribution
At X = 50 mm above Larger Burner
Top, in the Vertical Center Plane.
Sears Kenmore Series 71731.

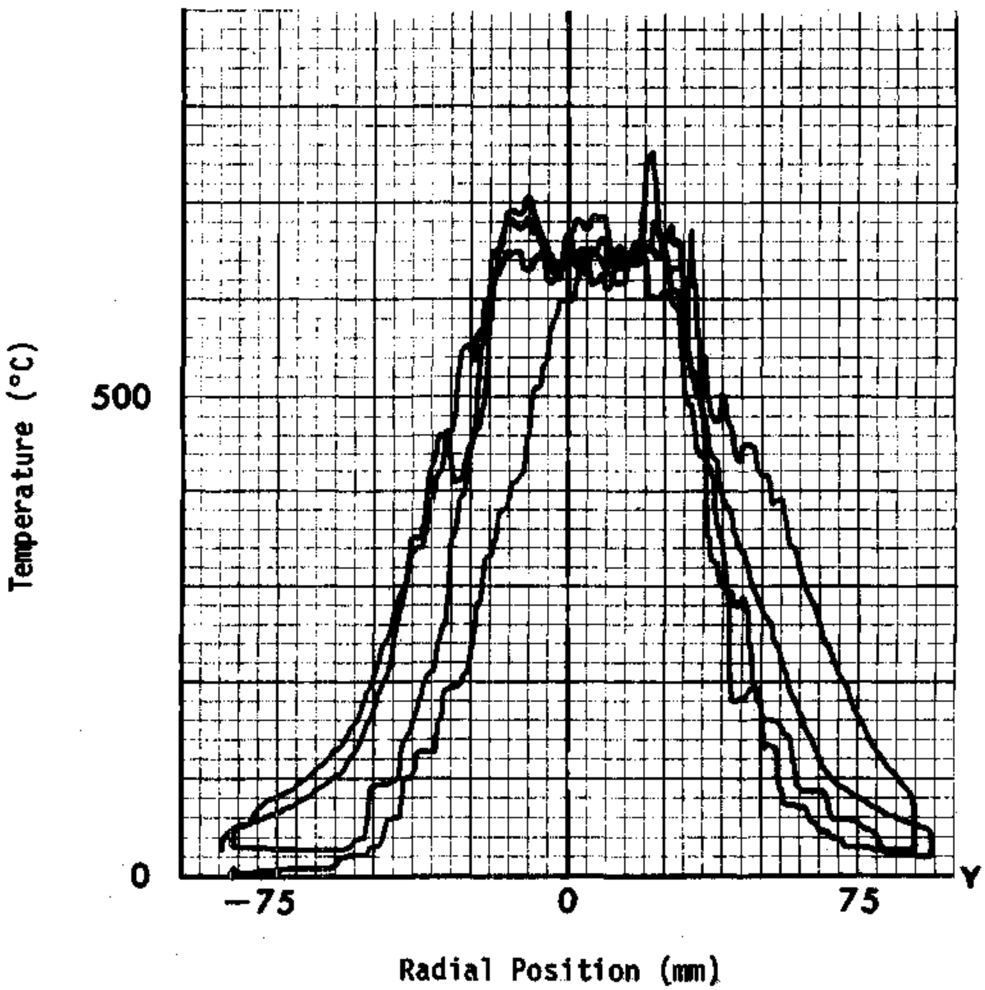

Figure 55. Temperature Distribution
At X = 75 mm above Larger Burner
Top, in the Vertical Center Plane.
Sears Kenmore Series 71731.

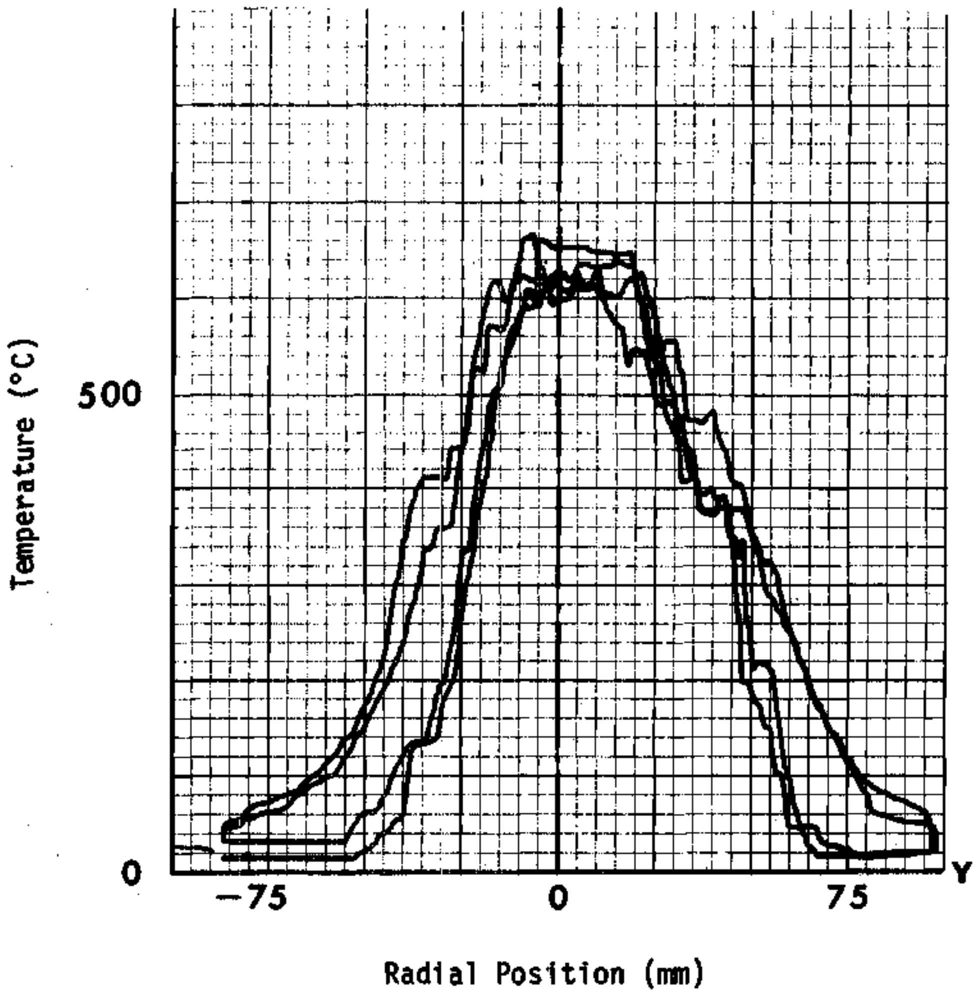

Figure 56. Temperature Distribution At X = 100 mm above Larger Burner Top, in the Vertical Center Plane. Sears Kenmore Series 71731.

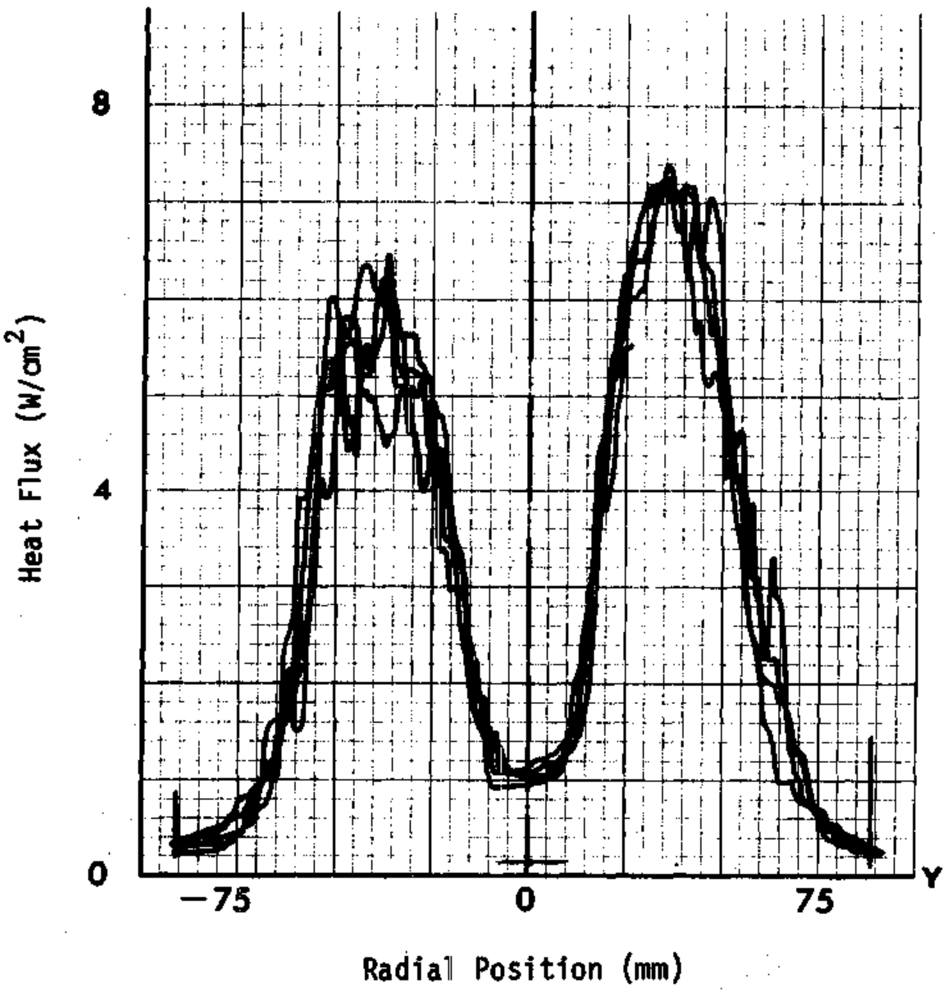

Figure 57. Heat Flux Distribution
At X = 25 mm above Larger Burner
Top, in the Vertical Center Plane.
Sears Kenmore Series 71731.

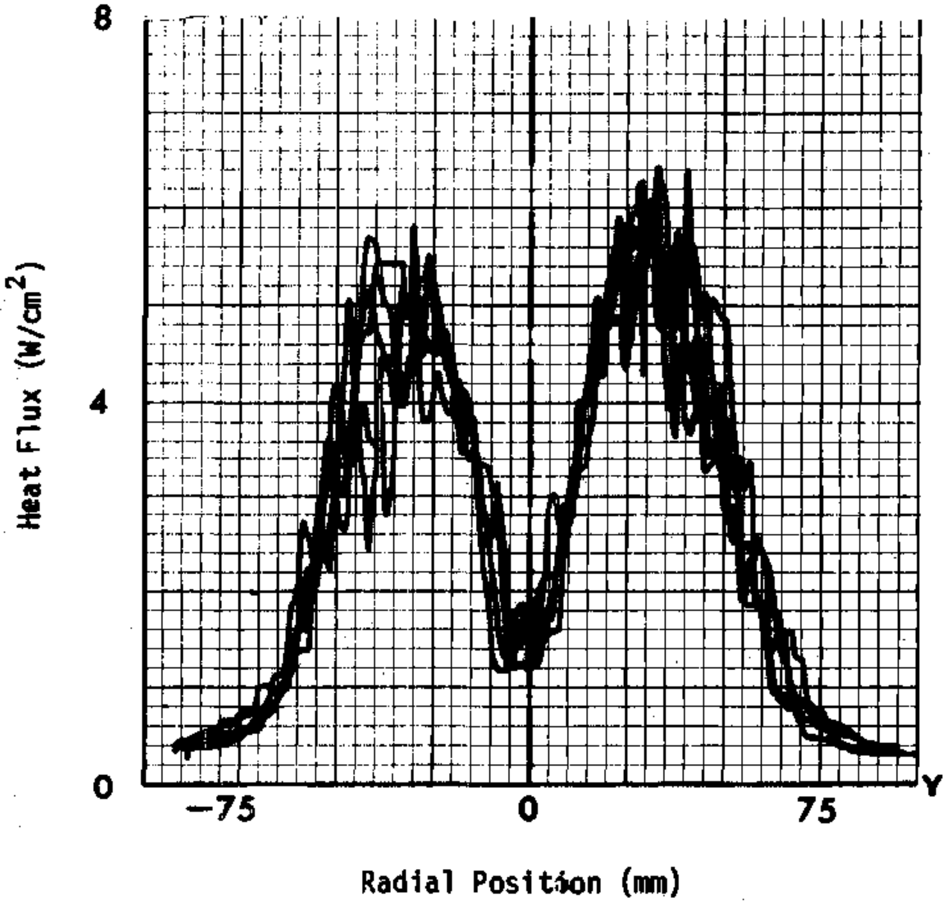

Figure 58. Heat Flux Distribution
At X = 37.5 mm above Larger Burner Top, in the Vertical Center Plane. Sears Kenmore Series 71731.

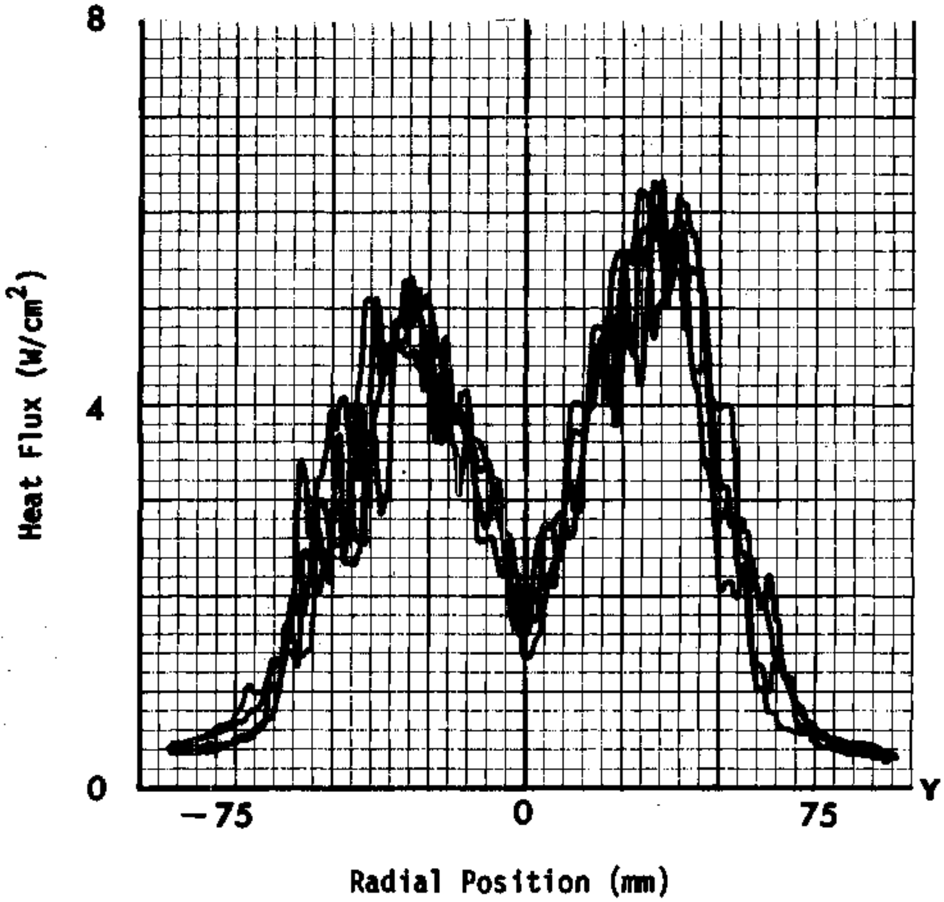

Figure 59. Heat Flux Distribution
At X = 50 mm above Larger Burner
Top, in the Vertical Center Plane.
Sears Kenmore Series 71731.

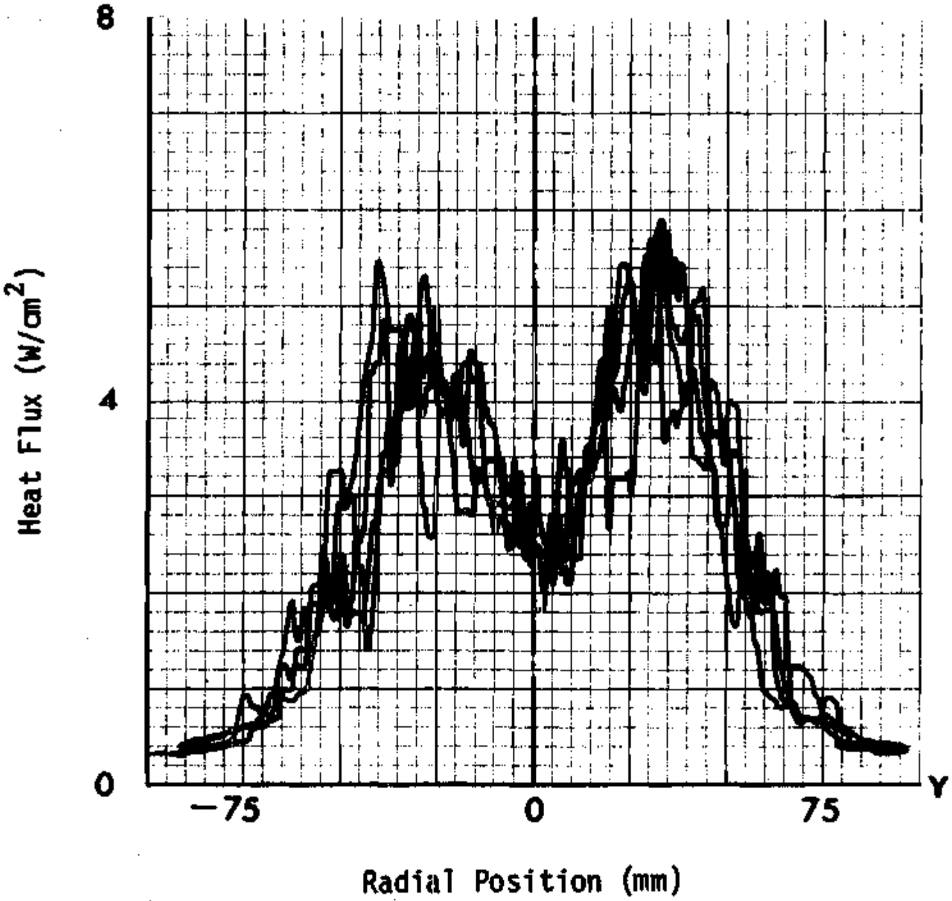

Figure 60. Heat Flux Distribution At X = 62.5 mm above Larger Burner Top, in the Vertical Center Plane. Sears Kenmore Series 71731.

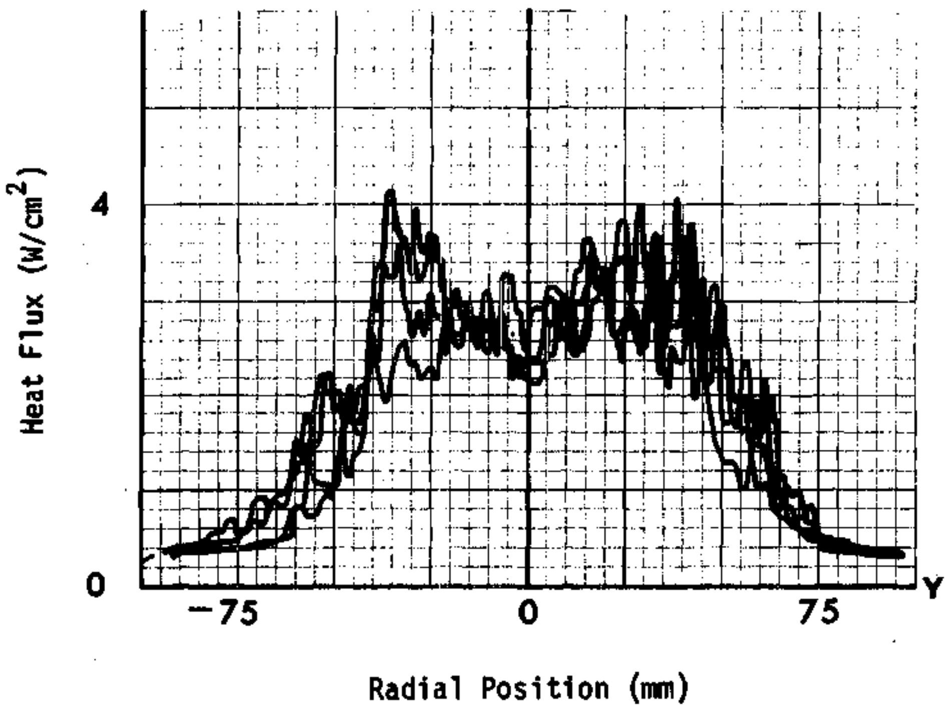

Figure 61. Heat Flux Distribution
At X = 87.5 mm above Larger Burner Top, in the Vertical Center Plane. Sears Kenmore Series 71731.

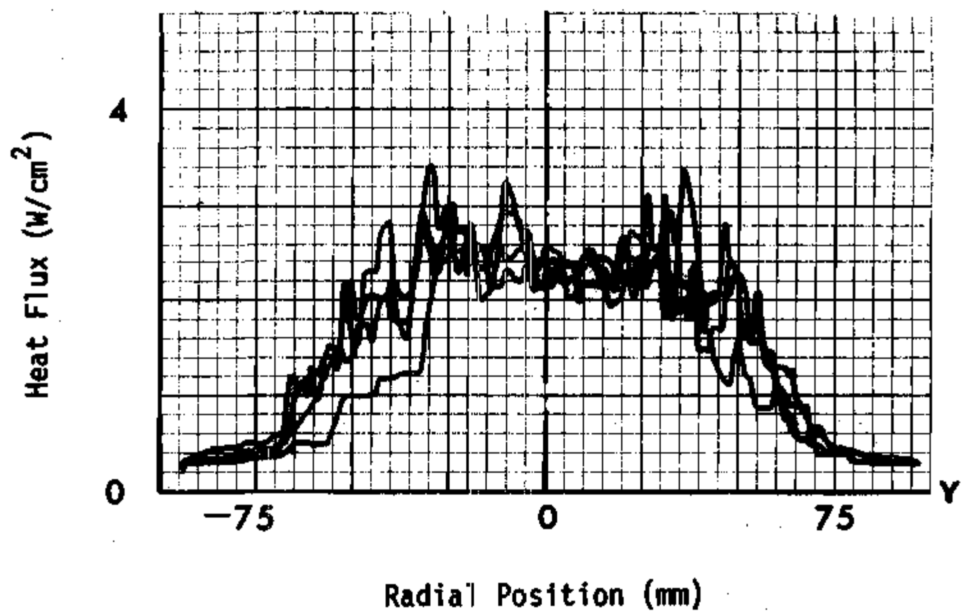

Figure 62. Heat Flux Distribution
At X = 112.5 mm above Larger Burner
Top, in the Vertical Center Plane.
Sears Kenmore Series 71731.

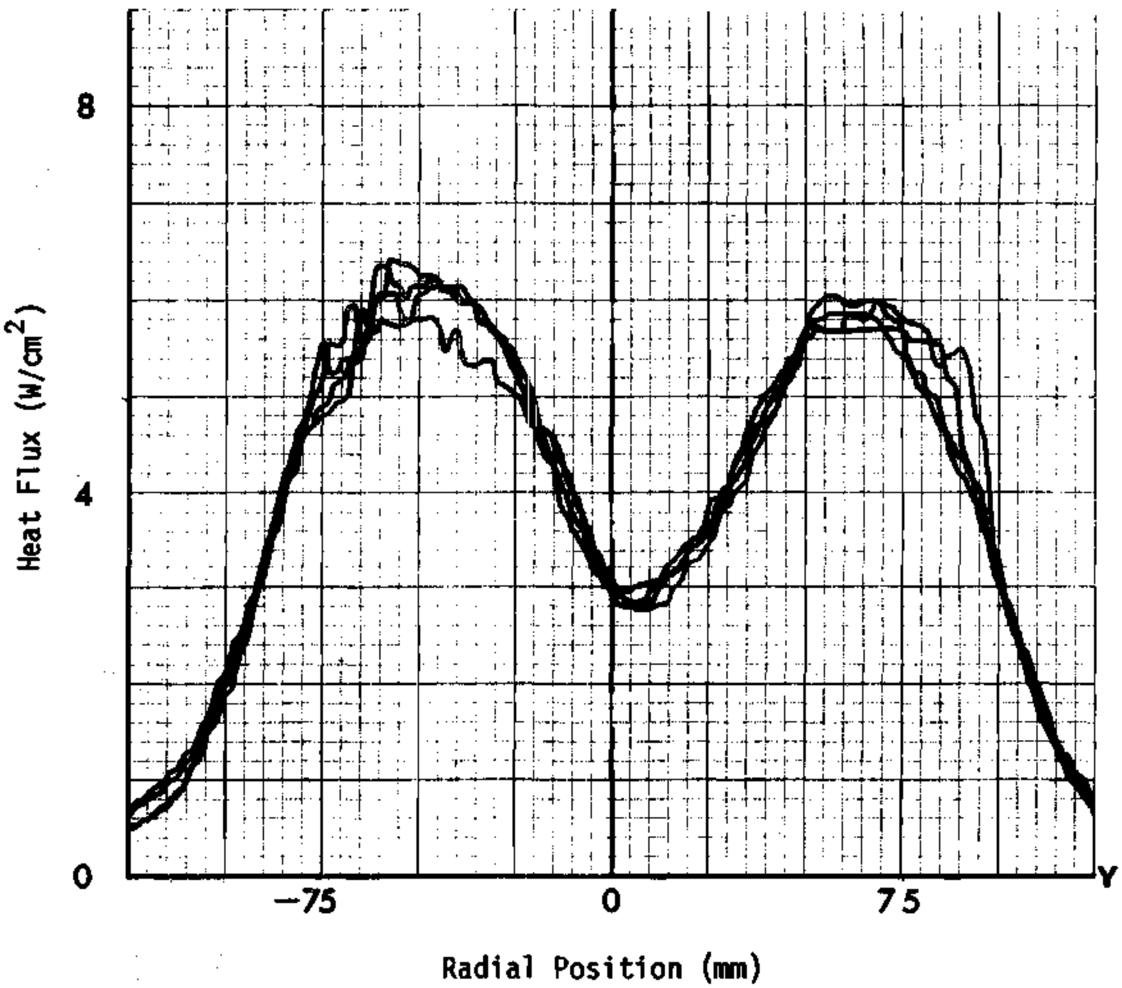

Figure 63. Heat Flux Distribution
At X = 12.5 mm above 2.6 KW Coil,
in the Vertical Center Plane.
Westinghouse Built-in Electrical
Range

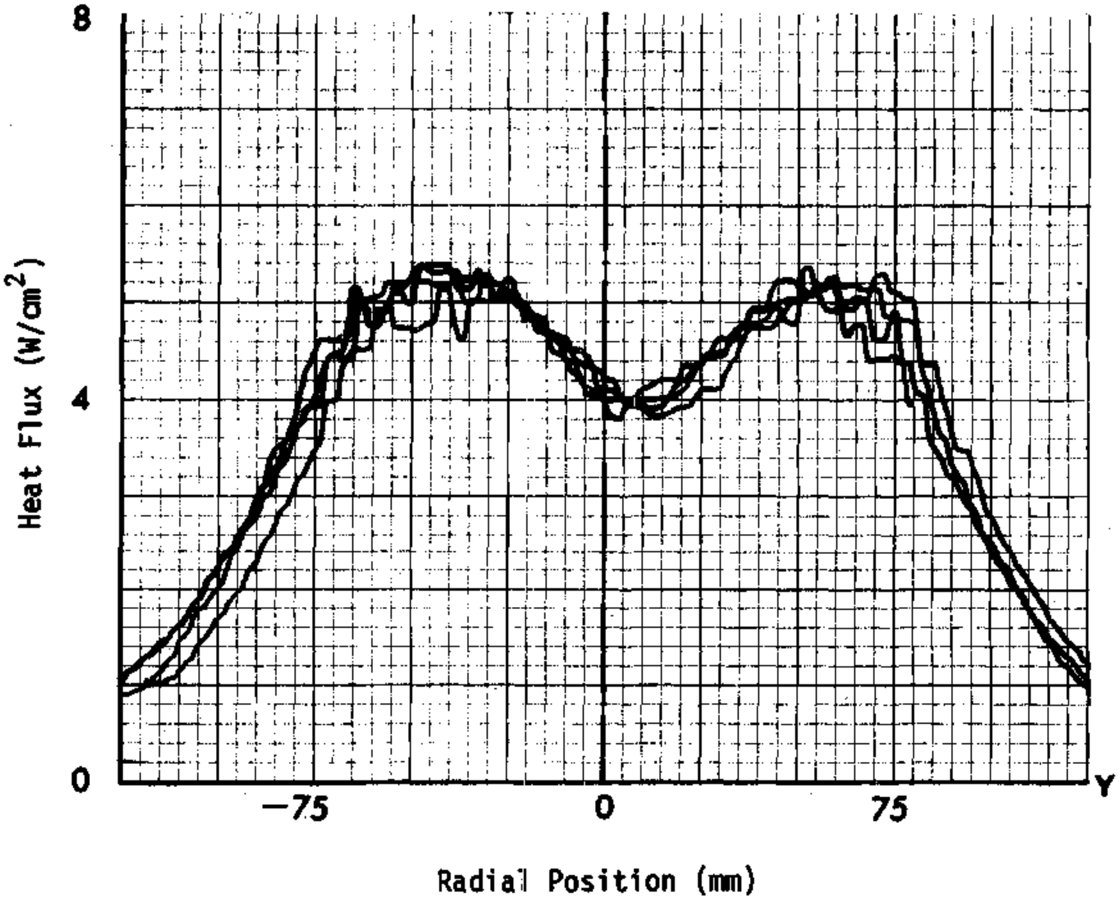

Figure 64. Heat Flux Distribution
At X = 25 mm above 2.6 KW Coil,
in the Vertical Center Plane.
Westinghouse Built-in Electrical
Range.

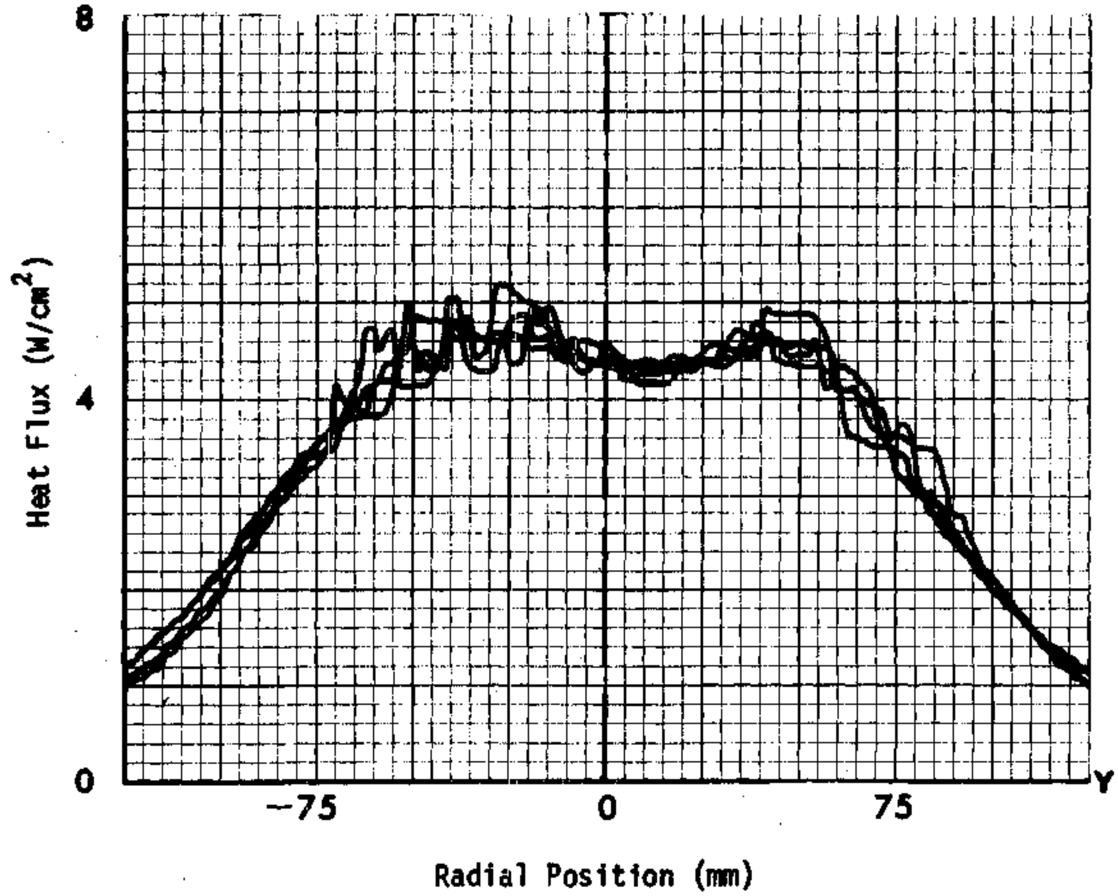

Figure 65. Heat Flux Distribution
At X = 37.5 mm above 2.6 KW Coil,
in the Vertical Center Plane.
Westinghouse Built-in Electrical
Range.

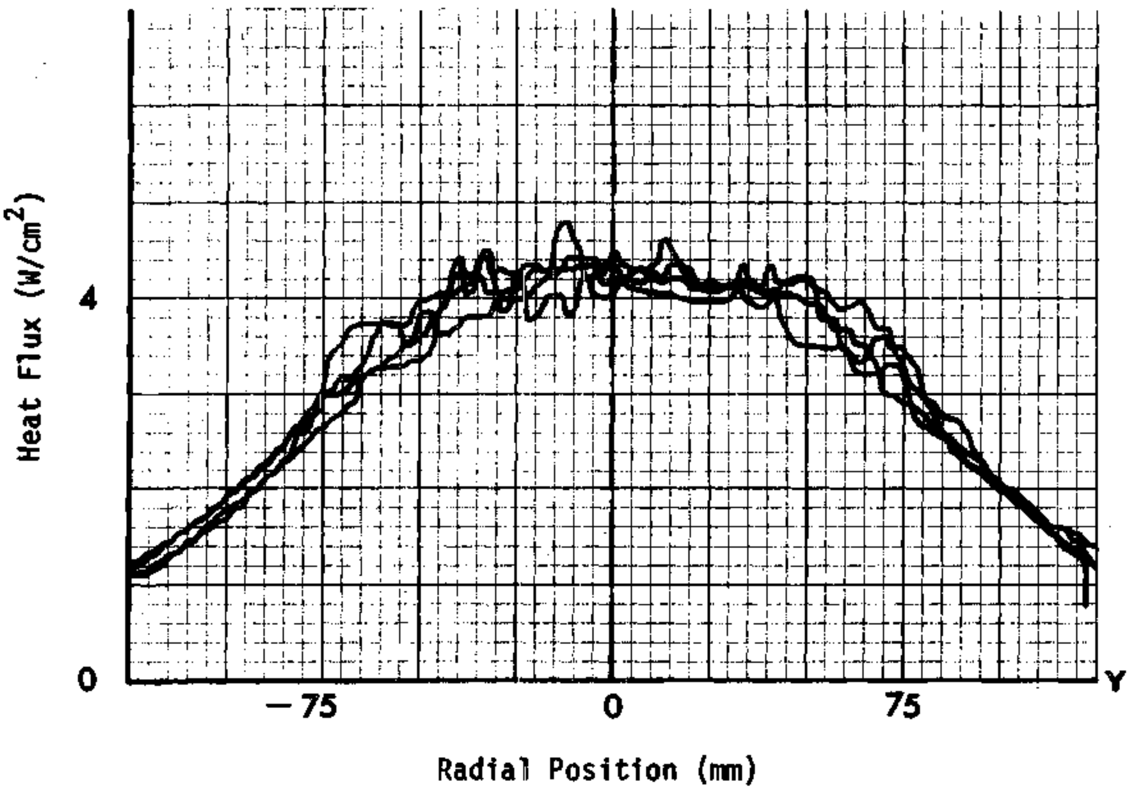

Figure 66. Heat Flux Distribution
At X = 50 mm above 2.6 KW Coil,
in the Vertical Center Plane.
Westinghouse Built-in Electrical
Range.

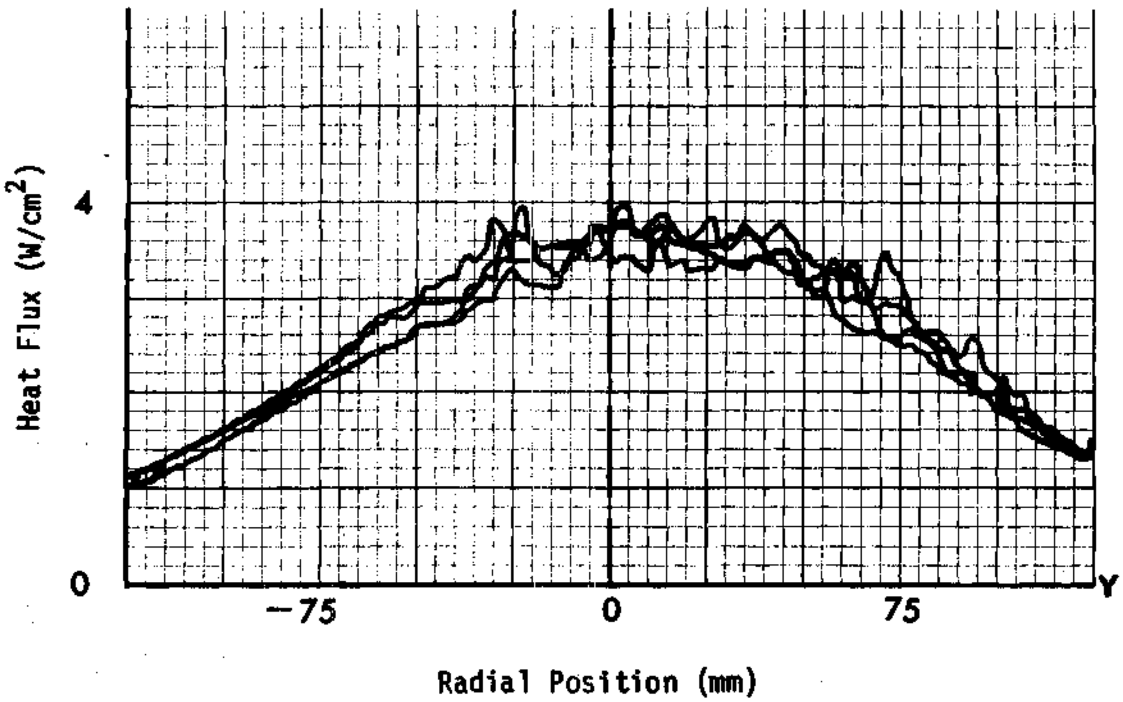

Figure 67. Heat Flux Distribution
At X = 75 mm above 2.6 KW Coil,
in the Vertical Center Plane.
Westinghouse Built-in Electrical
Range.

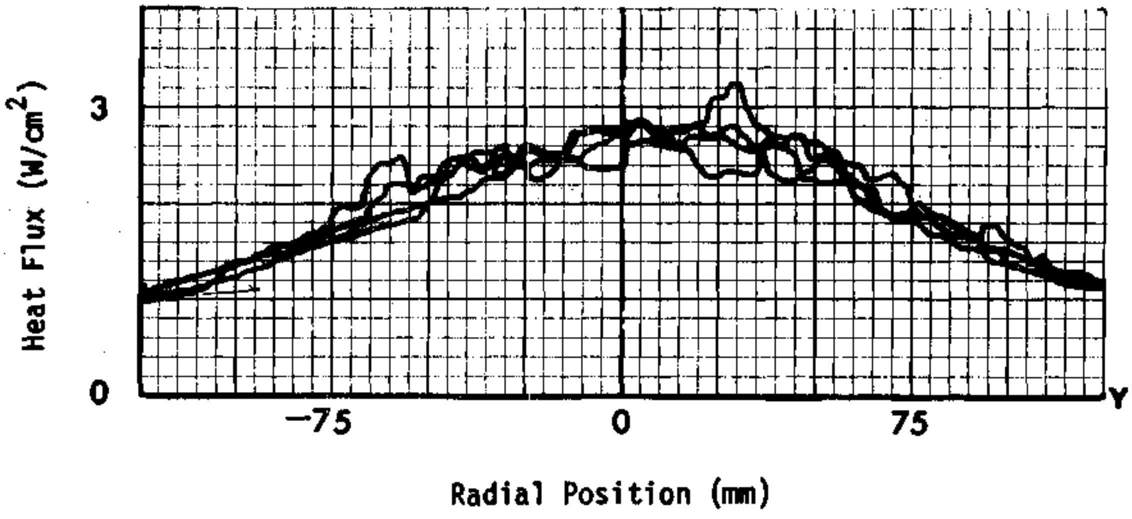

Figure 68. Heat Flux Distribution
At X = 100 mm above 2.6 KW Coil, in the Vertical Center Plane. Westinghouse Built-in Electrical Range.

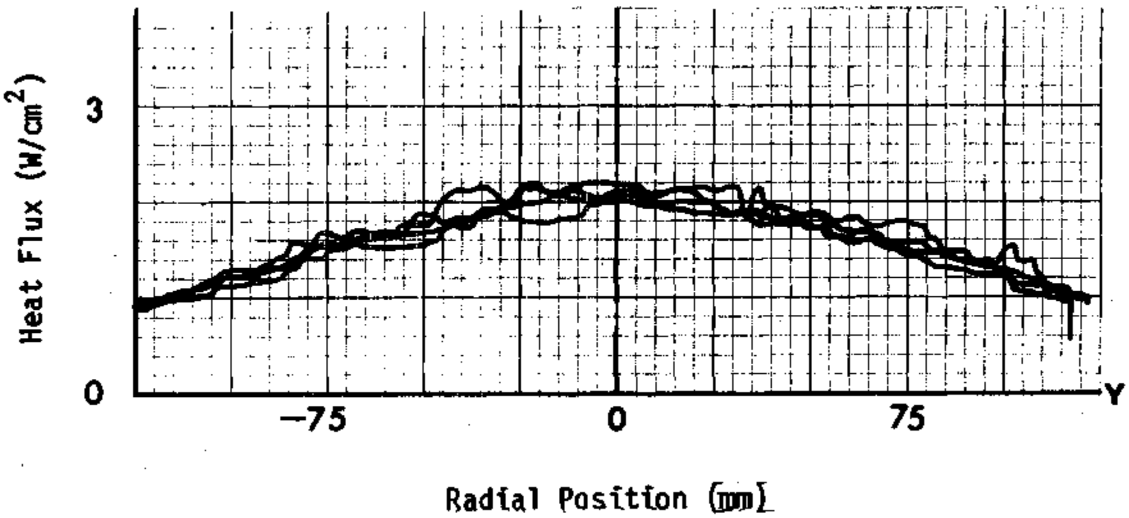

Figure 69. Heat Flux Distribution
At X = 125 mm above 2.6 KW Coil, in the Vertical Center Plane. Westinghouse Built-in Electrical Range.

APPENDIX C

CALIBRATION

The calibration of the sensors for heating source characterization is now described.

The heat flux sensor used for heating intensities measurements is a Hy-Cal Asymptotic water-cooled calorimeter, Model No. C-1301-A-60. The heat sensor is furnished with a certified factory calibration curve and its response is linear.

The temperature sensor was a thermocouple made of chromel-alumel wire with 0.020 inches in diameter. Its response was also linear.

The purpose of the calibration procedure is to relate the final signal to the measured quantities such that the X-Y plotter recording is congruent with the selected graph scales.

The linear response of the linear voltage differential transformer used to position the sensor with respect to a fixed reference was checked with a graduated scale. The X-output of the recorder was set such that 50 mm corresponded to 25 mm on the recording paper.

For the heat flux measurements, a differential voltmeter was used as a DC amplifier. The recorder response was determined by supplying inputs of 1 mV through 10 mV from a calibrated millivolt potentiometer. The response turned out to be linear. The Y-response of the plotter was adjusted to 2 watts/cm^2 per each 25 mm of recording paper. The amplifier gain is 1000 amplitude-ratio.

For the temperature measurements, the DV meter was not needed. The recorder was supplied with inputs of 10 mV through 50 mV, in 10 mV steps, from the calibrated potentiometer. The response was linear. The temperatures corresponding to those inputs were deduced from a thermocouples temperature table. The Y-output of the recorder was set to 200°C per 25 mm of the recording paper.

The calibration of the entire system was repeated for every ignition source tested.

Figure 70 below shows the final calibration curves for heat flux and temperature distributions.

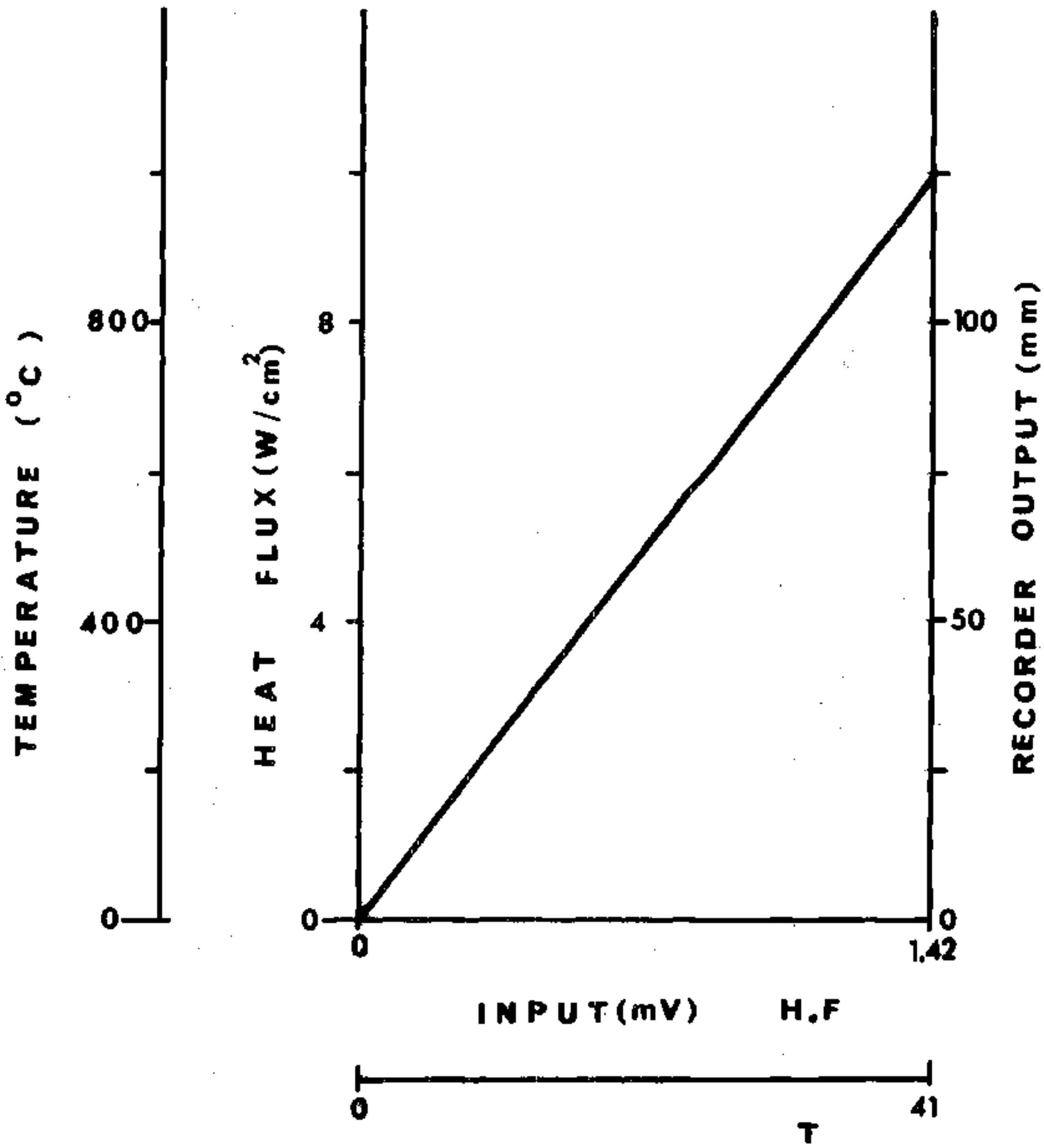

Figure 70. Calibration Curves for Heat Flux and Temperature Measurements

BIBLIOGRAPHY

1. National Commission on Fire Prevention and Control, "America Burning," May, 1973.

2. U. S. Department of Health, Education and Welfare, Fourth Annual Report, 1972, "Studies of Deaths, Injuries, and Economic Losses Resulting from Accidental Burning of Products, Fabrics, or Related Materials."

3. U. S. Department of Health, Education and Welfare, Third Annual Report, 1971, "Studies of Deaths, Injuries, and Economic Losses Resulting from Accidental Burning of Products, Fabrics, or Related Materials."

4. Reply from letter to Mr. Henry Tovey, NBS. Ignition Sources in FFACTS Automated File as of October 12, 1971.

5. Government-Industry Research Committee on Fabric Flammability, "Study of Hazards from Burning Apparel and the Relation of Hazards to Test Methods." A statement prepared by The Research Committee, Dr. E. Passaglia, Chairman, National Bureau of Standards, June 5, 1970.

6. Tribus, M., "Decision Analysis Approach to Satisfying the Requirements of the Flammable Fabrics Act," Paper presented at the Textile and Needle Trades Division, American Society for Quality Control, Greensboro, North Carolina, February 12, 1970.

7. Evans, R., Wulff, W., and Zuber, N., "The Study of Hazards from Burning Apparel and the Relation of Hazards to Test Methods," Research Proposal submitted by the School of Mechanical Engineering, Georgia Institute of Technology, to the Government Research Committee, July, 1970.

8. NBS Technical Note 596, "The Flammable Fabrics Program, 1970."

9. NBS Technical Note 749, "The Flammable Fabrics Program, 1971."

10. NBS Technical Note 810, "Fire Incidents Involving Sleepwear Worn by Children Ages 6-12."

11. NBS Technical Note 705. "Tabulation of Voluntary National Standards, Industry Standards, International Recommendations and Certification Programs for Consumer Products."

12. NBS Technical Note 762. "Tabulation of Voluntary Standards and Certification Programs for Consumer Products."

13. Alkidas, A., Hess, R., Wulff, W., and Zuber, N., "Study of Hazards from Burning Apparel and the Relation of Hazards to Test Methods," Final Report, submitted by the School of Mechanical Engineering, Georgia Institute of Technology, to the Government-Industry Research Committee on Flammable Fabrics, December, 1971.

14. Alkidas, A., Champion, E., Durbetaki, P., Giddens, W., Hess, R., Kumar, B., Naveda, O., Williams, P., and Wulff, W., "Study of Hazards from Burning Apparel and the Relation of Hazards to Test Methods," Second Final Report submitted by the School of Mechanical Engineering, Georgia Institute of Technology, to the Government-Industry Committee, December 31, 1972.

15. Fourt, L., Krasny, J., and Fisher, A., "Study of Hazards from Burning Apparel and the Relation of Hazards to Test Methods," Second Quarterly Report submitted by Gillette Company Research Institute to the Government-Industry Research Committee on Flammable Fabrics, June, 1971.

16. Williams, G., Metha, A., and Wong, F., "Measurement of Flammability and Burn Potential of Fabrics," Summary Report submitted by Massachusetts Institute of Technology to the National Science Foundation and to the Government-Industry Research Committee on Fabric Flammability, February, 1973.

17. Champion, E., "Determination of Fabrics Ignition Times Through Use of a Convective Heat Source Apparatus," M.S. Thesis, School of Mechanical Engineering, Georgia Institute of Technology, June, 1973.

18. Heskestad, G., "Ease of Ignition of Fabrics Exposed to Flaming Heat Sources," Third Quarterly Progress Report, submitted by Factory Mutual Research Corporation to the Government-Industry Research Committee on Fabric Flammability, October 1, 1972.

19. Fourt, L., "Study of Ignition and Exposure," Fourth Quarter Final Report, submitted by Gillette Research Institute to the Government-Industry Research Committee on Flammable Fabrics, December, 1971.

20. McDonald, K., Dardis, R., and Smith, B., "Flammable Fabrics and the Cost of Consumer Protection," Textile Research Journal, Vol. 41, 492-500, June, 1971.

21. Craw, A., "Analysis for Decision in the Office of Flammable Fabrics: The Level of the Standard," NBSIR-73-182, Report No. 18, April, 1973.

22. Trident Engineering Associates, Inc., "Study of Clothing Ignition Hazards from Gas and Electric Ranges," a report submitted to Office of Flammable Fabrics, National Bureau of Standards, May, 1972.

23. Gaskill, J., "Smoke Hazards and their Measurement, A Researcher's Viewpoint," Nuclear Science Abstract, UCRL-74573, 1974.

24. Information Council on Fabric Flammability Proceedings of First Annual Meeting, December 14, 1967.

25. Schaplowsky, A., "Deaths, Injuries, and Economic Losses from Accidental Burning of Products, Fabrics, or Related Materials," Paper presented at the Second Annual Meeting of the Information Council on Fabric Flammability, December, 1968.

26. Innes, R., Larson, D., and Lehman, S., "Causes of Severe Burns in Children Analysis of Clothing and Fabrics," paper presented at the Second Annual Meeting of the Information Council on Fabric Flammability, December, 1968.

27. McDonald, K., Dardis, R., and Smith, B., "An Investigation of Burn Injuries in an Urban Area-162 Cases," Journal Fire and Flammability, Vol. 2, 173-185, April, 1971.

28. NBS Technical Note 750, "Matches and Lighters in Flammable Fabric Incidents; The Magnitude of the Problem," December, 1972.

29. Alkidas, A., Hess, R., Kirkpatrick, C., Kirkpatrick, M., Bergles, A., Wulff, W., and Zuber, N., "Study of Hazards from Burning Apparel and the Relation of Hazards to Test Methods," Progress Report No. 1, Georgia Institute of Technology, April 1, 1971.

30. Natrella, M., Experimental Statistics, Handbook 91, United States Department of Commerce, National Bureau of Standards.

31. Finney, D., Probit Analysis, Cambridge University Press, 1947.

32. Hearle, J. and Peters, R., editors, Moisture in Textiles, Textile Book Publishers, Inc., The Textile Institute, Butterworths Scientific Publications, Manchester and London, 1960.

33. Vokvarka, F., "Full-Scale Burns in Urban Areas," Part I Fire Spread Between Structure, Final Report, submitted by IIT Research Institute to the Office of Civil Defense, June, 1969.

34. Heskestad, G., "Ease of Ignition of Fabrics Exposed to Flaming Heat Sources," Second Quarterly Progress Report, submitted by Factory Mutual Research Corporation to the Government-Industry Research Committee on Fabric Flammability, July 1, 1972.

35. Wulff, W. and Durbetaki, P., "Fabric Ignition and the Burn Injury Hazard," Paper presented at 1973 International Seminar on Heat Transfer from Flames, Trogir, Yugoslavia.

36. Hines, W. and Montgomery, D., Probability and Statistics, Ronald Press Co., New York, 1972.

37. Meyer, P., Introductory Probability and Statistical Applications, 2nd Edition, Addison-Wesley Co., 1970.

38. Alexander, H., Elements of Mathematical Statistics, J. Wiley and Sons, Inc., 1961.

39. Lipson, Ch. and Seth, N., Statistical Design and Analysis of Engineering Experiments, McGraw-Hill Co., 1973.

40. Tribus, M., Rational Descriptions, Decisions, and Designs, Pergamon Press, Inc., New York, 1969.

41. Raiffa, H. and Schlaifer, R., Applied Statistical Decision Theory, Harvard Business School, 1961.